

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) July 2014		2. REPORT TYPE Briefing Charts		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Experimental Investigation of Latent Heat Thermal Energy Storage for Bi-Modal Solar Thermal Propulsion			5a. CONTRACT NUMBER In-House		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Matthew R. Gilpin, David B. Scharfe, Marcus P. Young, Rebecca N. Webb			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER Q0CA		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQRS 1 Ara Drive Edwards AFB, CA 93524			8. PERFORMING ORGANIZATION REPORT NO.		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQR 5 Pollux Drive Edwards AFB, CA 93524			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RQ-ED-VG-2014-224		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Briefing Charts presented at 12th Annual International Energy Conversion Engineering Conference, Cleveland Ohio, 28-30 July 2014. PA#14391					
14. ABSTRACT A bi-modal solar thermal system capable of providing propulsive and electric power to a spacecraft has been identified as a promising architecture for microsatellites requiring a substantial ΔV . The use of a high performance thermal energy storage medium is the enabling technology for such a configuration and previous solar thermal studies have suggested the use of high temperature phase change materials (PCMs) such as silicon and boron. To date, developmental constraints and a lack of knowledge have prevented the inclusion of these materials in solar thermal designs and analysis has remained at the conceptual stage. It is the focus of this ongoing research effort to experimentally investigate using both silicon and boron as high temperature PCMs and enable a bi-modal system design which can dramatically increase the operating envelope for microsatellites. This paper discusses the current progress of a continued experimental investigation into a molten silicon based thermal energy storage system. Using a newly operational solar furnace facility, silicon samples have been melted and results indicate that volumetric expansion during freezing will be the primary difficulty in using silicon as a PCM. Further experimental studies using different materials and test section fill factors have identified potentially reliable experimental conditions at the expense of energy storage density. In addition to conducting experiments, a concurrent computational effort is underway to produce representative models of the experimental system. The current models generally follow experimental results; however, difficulties still remain in determining high temperature material properties and material interactions. This paper also discusses the future direction of this research effort including modeling improvements, analysis of convective coupling with phase change energy storage and potential facility improvements.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 64	19a. NAME OF RESPONSIBLE PERSON Marcus Young
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NO (include area code) 661-275-6264

Experimental Investigation of Latent Heat Thermal Energy Storage for Bi-Modal Solar Thermal Propulsion

Matthew R. Gilpin, USC

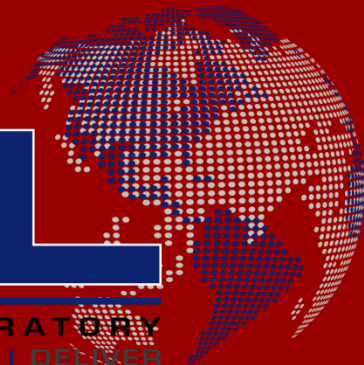
David B. Scharfe, ERC, Inc.

Marcus P. Young, ARFL/RQRS

Rebecca N. Webb, UCCS

AFRL

THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER



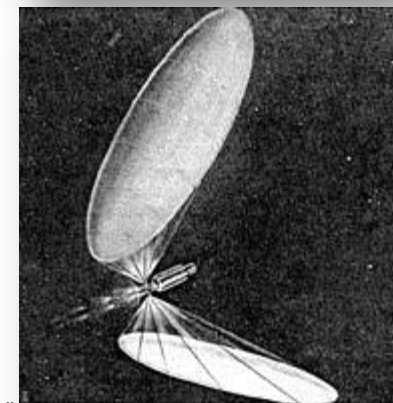
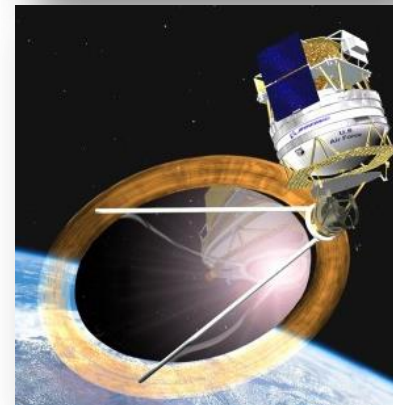
- Solar thermal propulsion (STP) has over 50 years of developmental history and offers a compromise between thrust and efficiency

Monoprop. Rocket
~230s Isp

Solar Thermal
300-700s Isp

Electric
>1000s Isp

- No solar thermal spacecraft have been flown to date
 - Novel (i.e. “awkward”) architecture
 - Scale of proposed systems
 - Adverse impact as a “demo” mission
- A bi-modal solar thermal microsatellite has the potential to greatly increase the operating envelope of the platform
- The development of **high temperature latent heat thermal energy storage** is currently an enabling technology

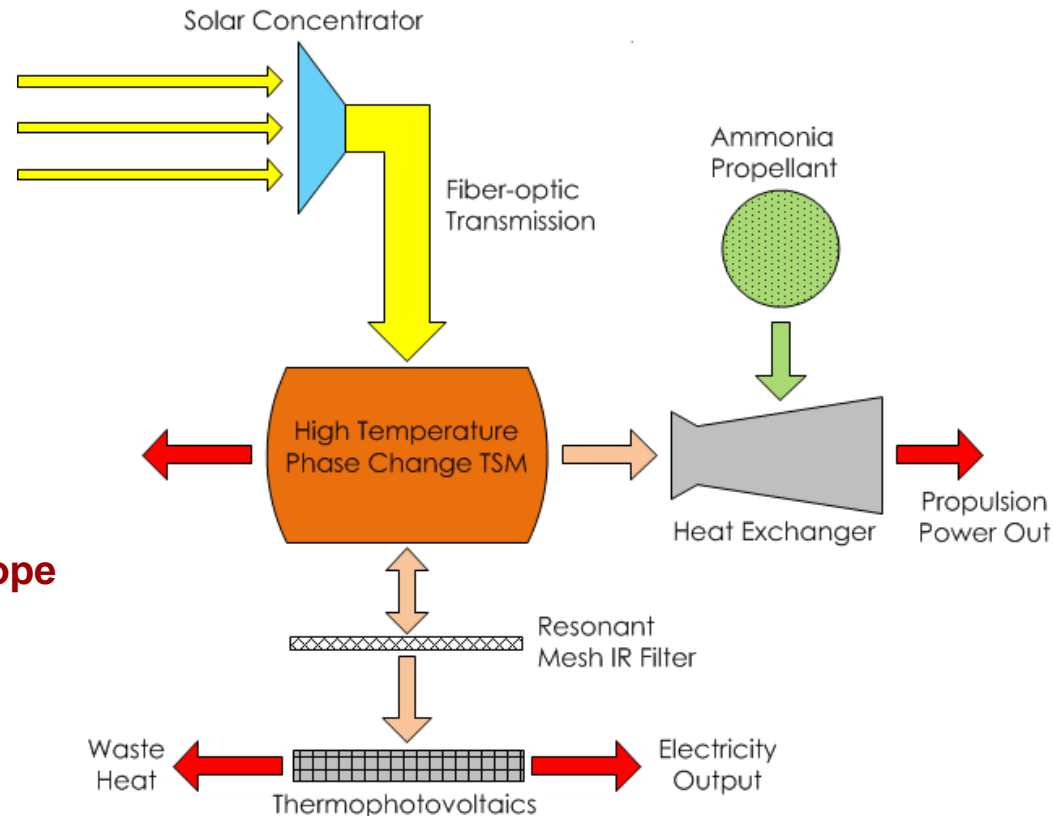


- A review by the AFRPL Advanced Concepts Group identified STP as a promising candidate for high performance microsatellite missions (*Scharfe 2009*)
- A **bi-modal microsatellite** configuration is proposed and further study is recommended
- Microsatellite scaling distinguishes STP
- Large ΔV (> 1 km/s) possible

Expand the Microsatellite Operating Envelope

- Expand possible “piggy-back” launch options
- GEO Insertion: ~ 1760 m/s
- Near Escape Missions: $\sim 770 - 1770$ m/s

Possible with EP, however, STP offers a much shorter burn time and higher maneuverability





☐ **Solar Concentrators**

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☐ **Fiber Optic Coupling**

- High transmission efficiency
- High pointing accuracy

☐ **Thermal-Electric Conversion**

- Operational at high temperatures
- High specific power

☐ **Advanced Insulation**

- Low Mass
- High Temperature

☐ **High Temperature Storage Material**

- Matches STP propulsion temperatures
- High energy density ($> 1000+ \text{ kJ/Kg}$)

☐ **Compatible / Effective RAC**

- Long term compatibility
- Effective energy coupling

☒ **Solar Concentrators**

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☐ **Fiber Optic Coupling**

- High transmission efficiency
- High pointing accuracy

☐ **Thermal-Electric Conversion**

- Operational at high temperatures
- High specific power

☐ **Advanced Insulation**

- Low Mass
- High Temperature

☐ **High Temperature Storage Material**

- Matches STP propulsion temperatures
- High energy density ($> 1000+ \text{ kJ/Kg}$)

☐ **Compatible / Effective RAC**

- Long term compatibility
- Effective energy coupling

- Thin PMA (JAXA) “flight ready” concentrators achieve 200 g/m^2 and C. ratios $> 10,000:1$
- Inflatables (AFRPL, SRS) can achieve $< 1 \text{ kg/m}^2$ and have been reported as being “optical quality”
- Large rigid structures (NASA SD, ISUS) are listed at approx. 3 kg/m^2 including mounting, tracking, and deployment
- Microsatellite scale system only requires $< 2 \text{ m}^2$



Sahara 2004



SRS Technologies

☒ Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☒ Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

☐ Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

☐ Advanced Insulation

- Low Mass
- High Temperature

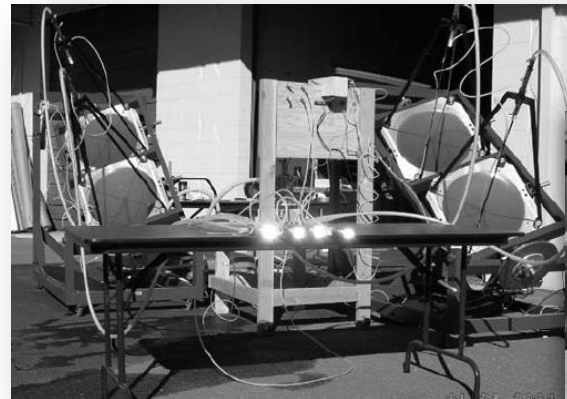
☐ High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density ($> 1000+ \text{ kJ/Kg}$)

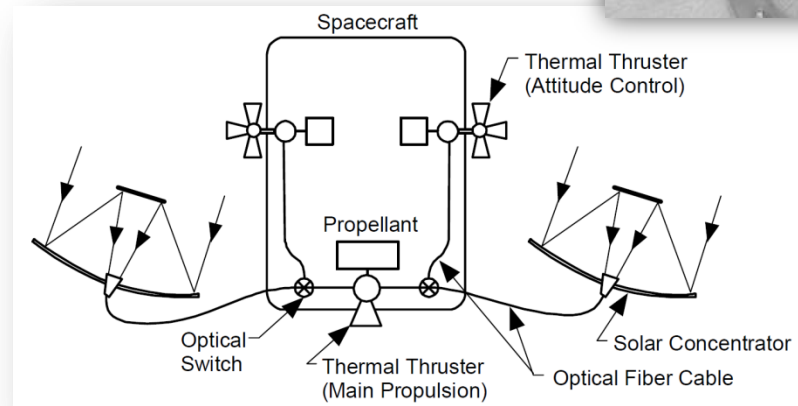
☐ Compatible / Effective RAC

- Long term compatibility
- Effective energy coupling

- Current lab systems operate at 35% η_{total}
- Estimated 70% η_{total} for a space qualified system from better materials selection
- Pointing accuracy of approx. 0.1° required



Nakamura 2004



☒ Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☒ Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

☒ Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

☐ Advanced Insulation

- Low Mass
- High Temperature

☐ High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density ($> 1000+$ kJ/Kg)

☐ Compatible / Effective RAC

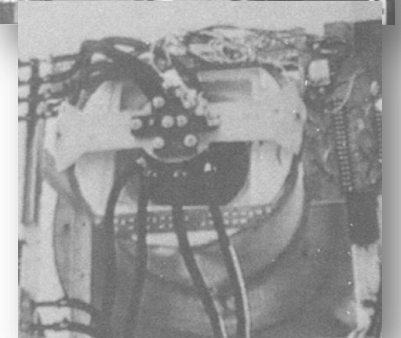
- Long term compatibility
- Effective energy coupling

- Thermophotovoltaics are the strongest candidate
- Operation targets properly matched to solar thermal temperatures.
- Closed Brayton and thermionics scale poorly for microsats
- 15 W/kg in current systems, including radiator

Edtek



McDonnell Douglas



☒ Solar Concentrators

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☒ Fiber Optic Coupling

- High transmission efficiency
- High pointing accuracy

☒ Thermal-Electric Conversion

- Operational at high temperatures
- High specific power

☒ Advanced Insulation

- Low Mass
- High Temperature

☐ High Temperature Storage Material

- Matches STP propulsion temperatures
- High energy density (> 1000+ kJ/Kg)

☐ Compatible / Effective RAC

- Long term compatibility
- Effective energy coupling

Material	k_{th} @ 1000 C (W/mK)	k_{th} @ 1500 C (W/mK)	k_{th} @ 2000 C (W/mK)	Density (g/cm ³)
Silicon Carbide	45	30	25	3.2
Boron Nitride	17-33	22.5	18	1.8
Alumina	6.5	6.6	--	3.8
Zirconia	2	2.5	3	5.5
ONRL CBCF	0.17	0.2	0.26	0.2
Calcarb CBCF	0.2	0.35	0.65	0.18
Aerogel Filled Graphite Foams	0.25	0.4	0.75	0.07
Mo - ZrO ₂ Multifoil	0.001	0.05	0.1	1.4

- Must operate between **1500 – 2600 K**

• Carbon Bonded Carbon Fiber

- Can draw from NASA RTG development
- Carbon foams with filler to limit radiation loss currently offered by ULTRAMET

• Low Emissivity Vacuum Gap

- Typically the first stage in a TPV system
- Mo/ZrO₂ multifoil blankets also produced for RTGs

• Ceramic Doped Aerogels

- Underdevelopment with JPL, RZSM, and RQRS



☒ **Solar Concentrators**

- 10,000 :1 Concentration Ratio
- Low mass and deployable

☒ **Fiber Optic Coupling**

- High transmission efficiency
- High pointing accuracy

☒ **Thermal-Electric Conversion**

- Operational at high temperatures
- High specific power

☒ **Advanced Insulation**

- Low Mass
- High Temperature

☐ **High Temperature Storage Material**

- Matches STP propulsion temperatures
- High energy density ($> 1000+ \text{ kJ/Kg}$)



☐ **Compatible / Effective RAC**

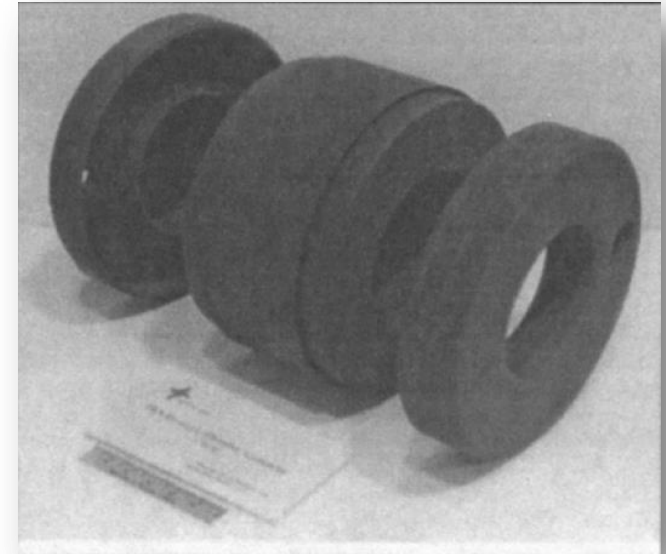
- Long term compatibility
- Effective energy coupling



To date, all STP systems have used sensible heat thermal energy storage

Material	T_{melt} [K]	C_p @ 2500 K [kJ/kgK]	ΔT Required for 1 MJ/kg
Graphite	3923	2.15	475
Boron Carbide	2700	2.68	380
Silicon Carbide	2818	1.01	740
Boron Nitride	3273	1.98	510

- Simplified engineering suitable for time constrained development – Low TRL level of other options
- “...moderate yet acceptable performance” - Kennedy 2002



ISUS Data Analysis

- Seven minute “steady” burn corresponds to an “effective” energy storage density of **0.5 MJ/kg**
- When the RAC achieves 1 MJ/kg, **exit temp** has dropped by **> 25%** and **Isp** has dropped by **15%**
- ISUS spec for thermionic hot shoe temperature was 1900 – 2200 K. If allowed for a radiantly coupled TPV system, this would correspond to a **> 50% decrease** in power output

Potential High-Temp Phase Change Materials

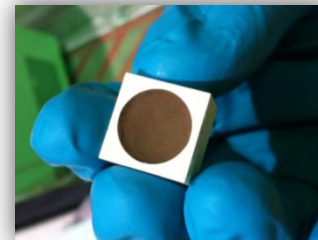
Material	T_{melt} [K]	ΔH_{fus} [MJ/kg]	$k_{\text{th @ } T_{\text{melt}}}$ [W/mK]
MgF ₂	1536	0.94	3.8
Beryllium	1560	1.31	69
Silicon	1687	1.79	20
Nickel	1728	0.3	83
Scandium	1814	0.31	16
Chromium	2180	0.4	48
Vanadium	2183	0.45	51
Boron	2350	4.6	10
Ruthenium	2607	0.38	80
Niobium	2750	0.29	82
Molybdenum	2896	.38	84

Silicon



- Moderate Performance
- 330s I_{sp}

Boron



- High Performance
- 390s I_{sp}

Bi-Modal System Performance Parameters 100 kg Microsatellite - 100 W continuous power draw

Silicon System		
Thermal Collection	5.3	kg
Thermal Storage	3.3	kg
Power	6.7	kg
Propellant	36.7	kg
Tankage / Thruster	6.1	kg
Prop. / Power Total	58.2	kg
Payload Mass	41.8	kg

$M_{\text{Propulsion \& Power}} \sim 58\%$

1500 m/s ΔV

Thermal Collection

- Primary concentrator
- Support structure
- Fiber optics

Thermal Storage

- PCM
- Insulation

Power

- TPV cells
- Radiator Panels

Propellant

- Liquid Ammonia

Tankage / Thruster

- Titanium Tank
- Piping
- Nozzle and Heat Exchanger
- Reinforcements

Bi-Modal System Performance Parameters
100 kg Microsatellite - 100 W continuous power draw

Silicon System		
Thermal Collection	5.3	kg
Thermal Storage	3.3	kg
Power	6.7	kg
Propellant	36.7	kg
Tankage / Thruster	6.1	kg
Prop. / Power Total	58.2	kg
Payload Mass	41.8	kg

$M_{\text{Propulsion \& Power}} \sim 58\%$

1500 m/s ΔV

Boron System		
Thermal Collection	5.4	kg
Thermal Storage	1.9	kg
Power	6.7	kg
Propellant	38.0	kg
Tankage / Thruster	6.3	kg
Prop. / Power Total	58.2	kg
Payload Mass	41.8	kg

$M_{\text{Propulsion \& Power}} \sim 58\%$

1850 m/s ΔV

Thermal Collection

- Primary concentrator
- Support structure
- Fiber optics

Thermal Storage

- PCM
- Insulation

Power

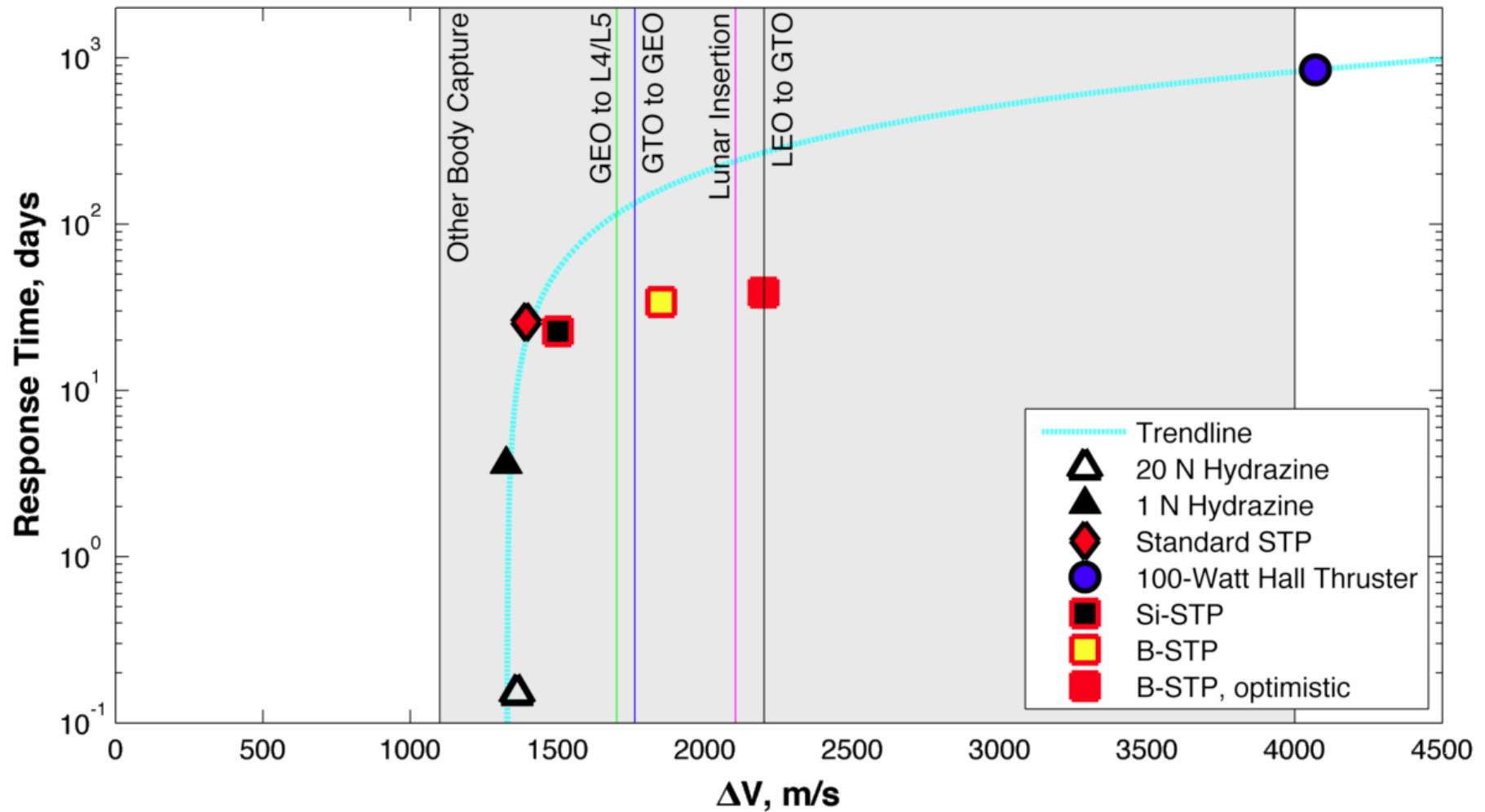
- TPV cells
- Radiator Panels

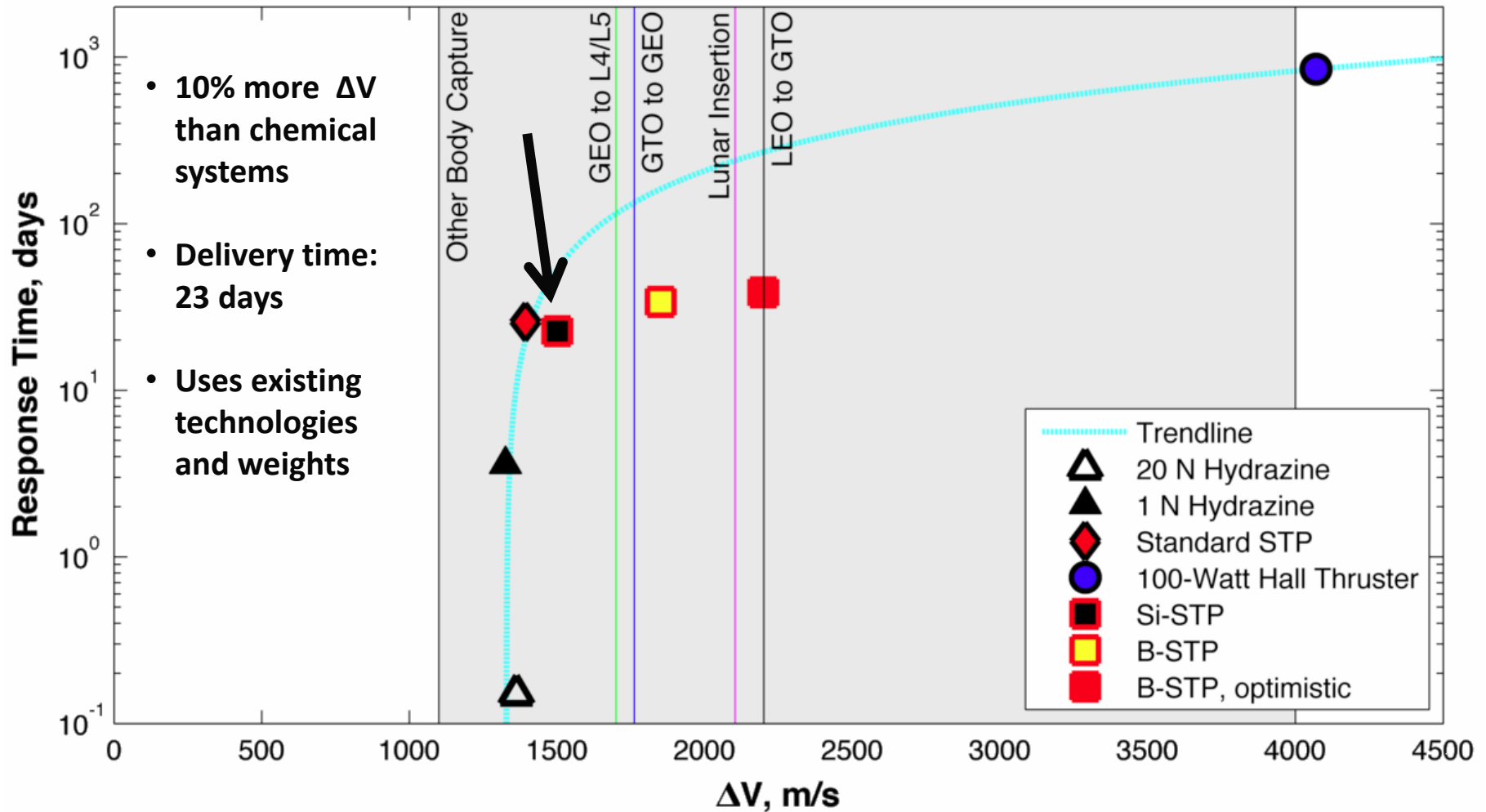
Propellant

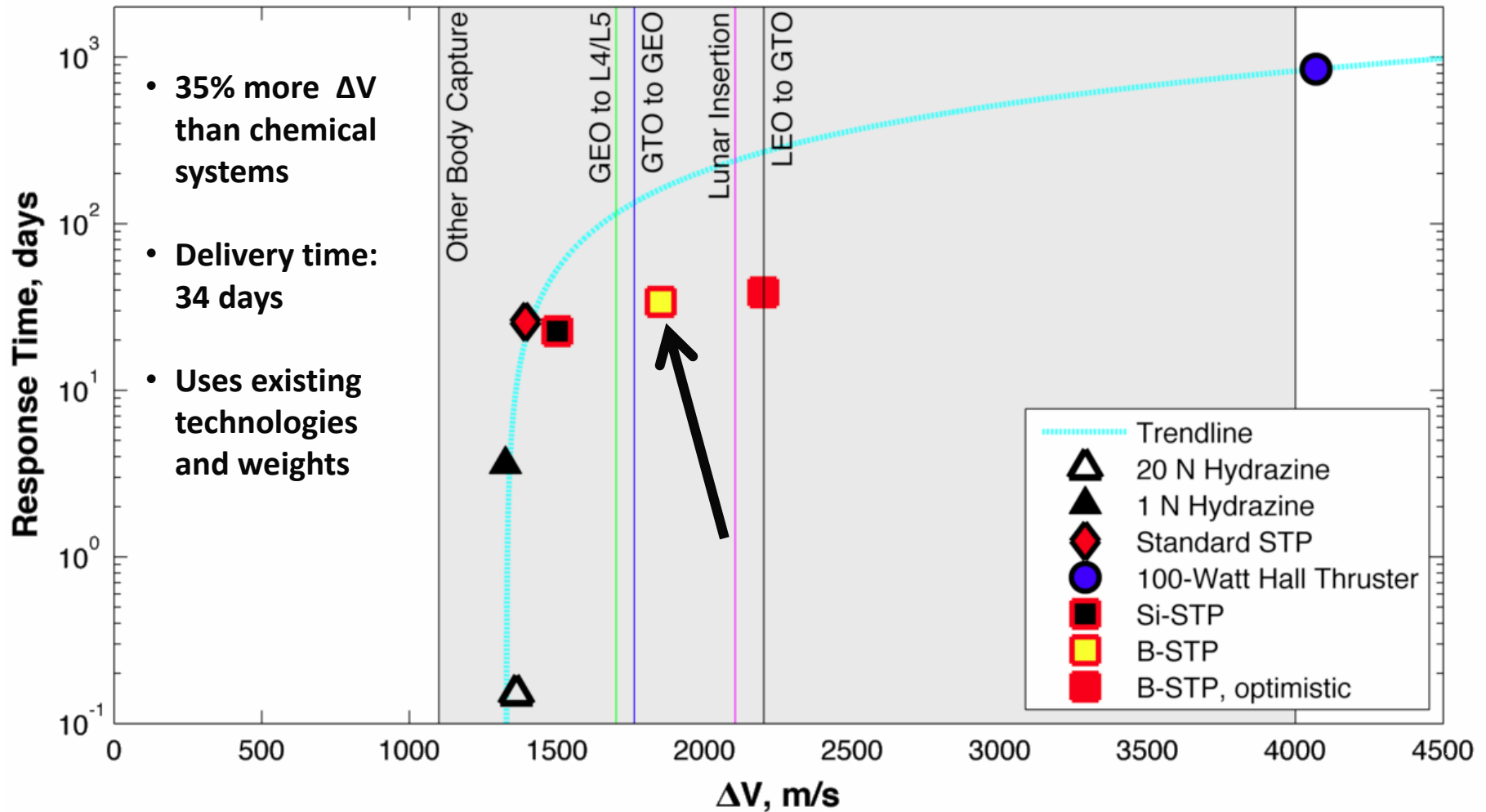
- Liquid Ammonia

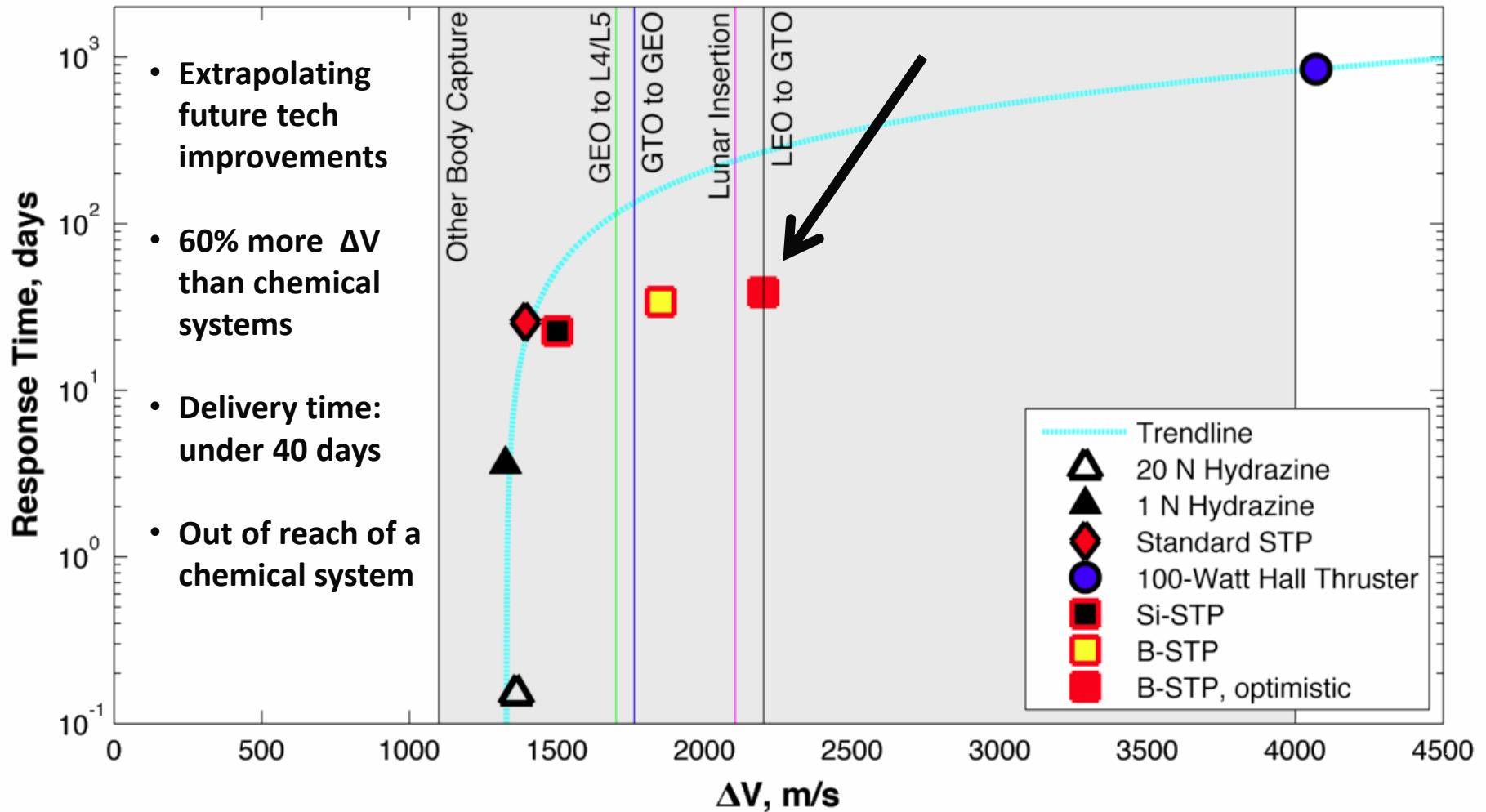
Tankage / Thruster

- Titanium Tank
- Piping
- Nozzle and Heat Exchanger
- Reinforcements









Demonstrate a Proof of Concept Latent Heat Thermal Energy System Using Molten Silicon

- **No experiments to-date directly targeting energy storage applications**
- **Mentioned as a potential buffer / storage material for TPVs**
 - Woodall 1982 - IBM patent
 - Chubb et al. 1996 - white paper, “ideal storage material”
- **Brief mentions in the solar thermal literature**
 - Laug et al. 1995 – Initial bi-modal study
 - Kennedy 2002 – TRL level not sufficient
 - Abbot 2001 – Trade study

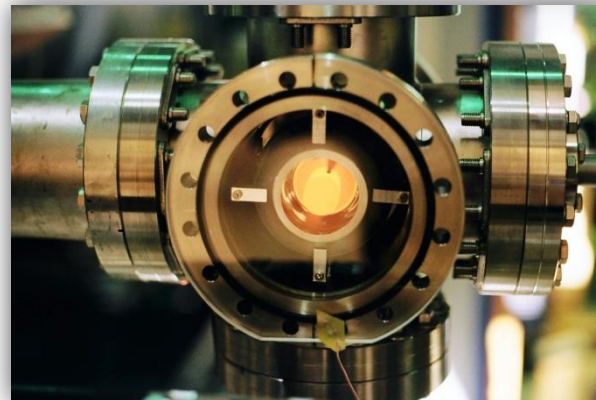
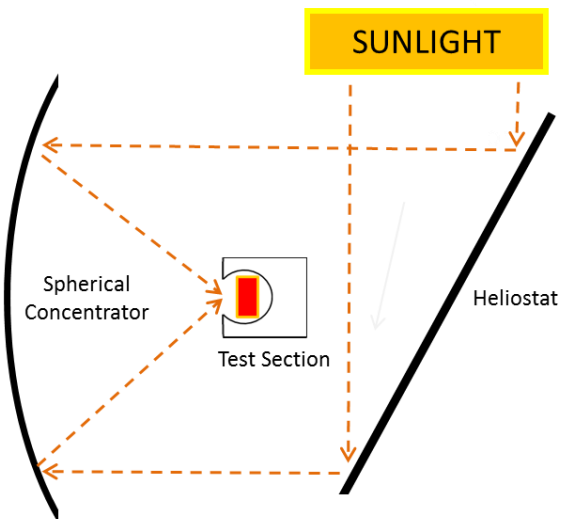
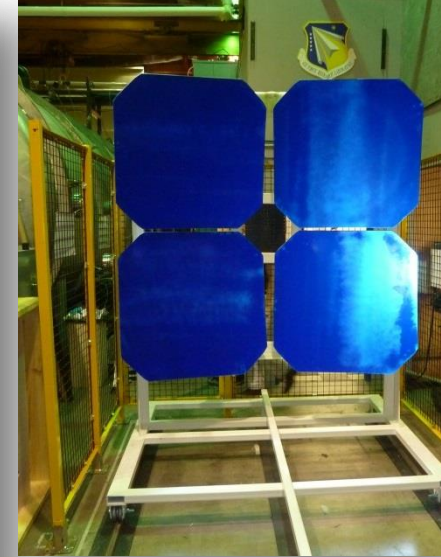
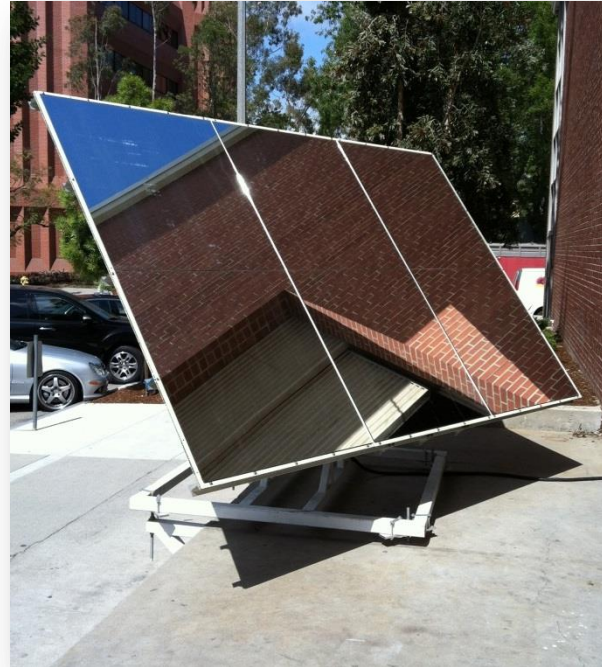
1) Facility Development

2) Materials Selection

3) Modeling Capability and Analysis

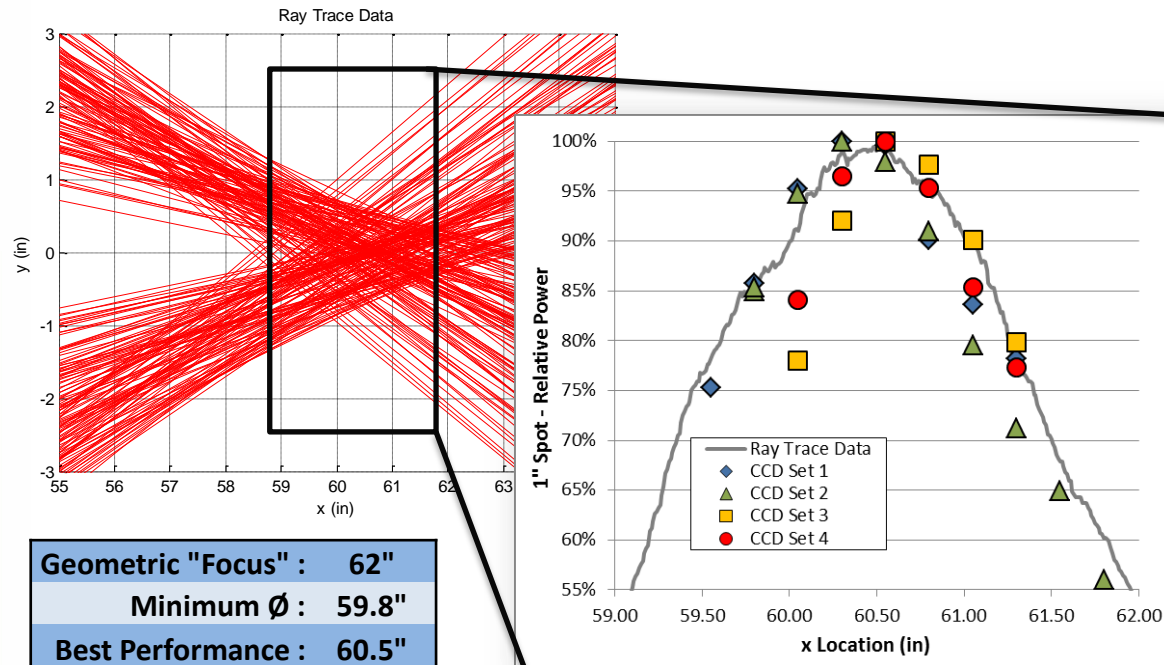
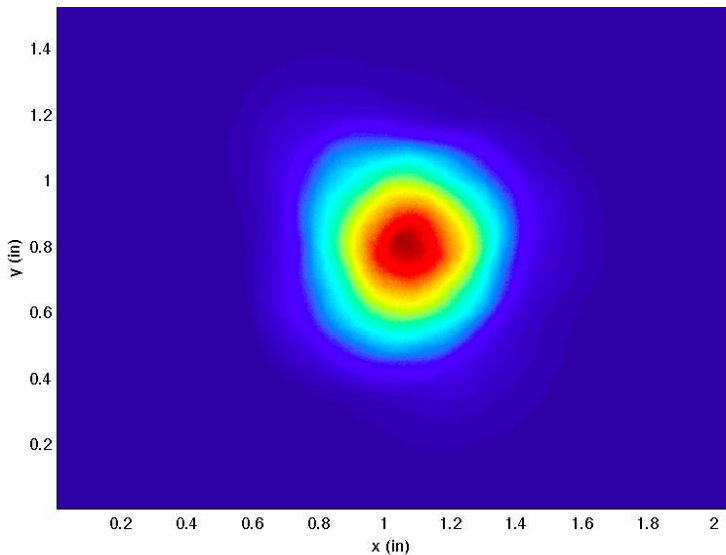
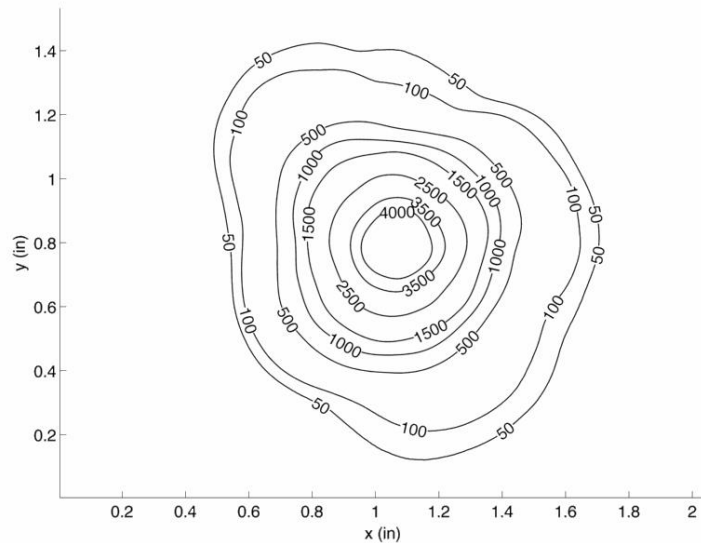
4) Experimental Demonstration

- First-surface spherical concentrator
 - $r_c = 124''$
 - SiO_2 coating optimized to the solar spectrum
 - Manufactured by DOTI Optics
- 3600 in² usable concentrator area
- 12 ft x 8 ft computer controlled heliostat
- COTS and surplus components
- Delivers 800-1100 W in a 1" spot

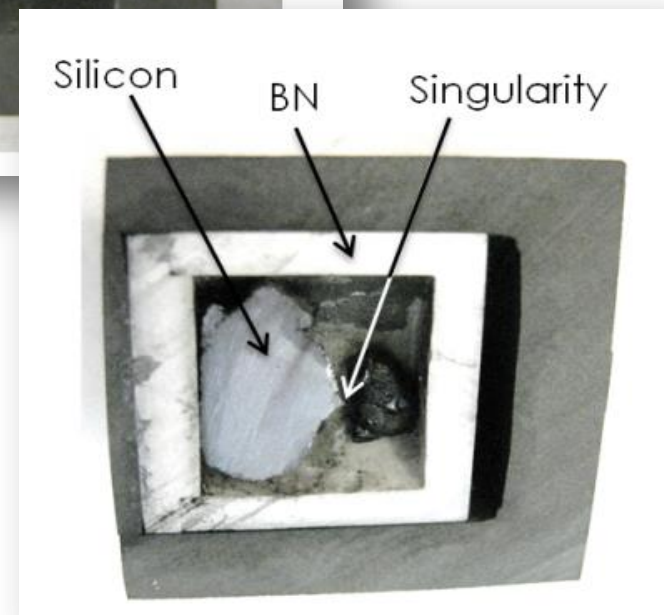
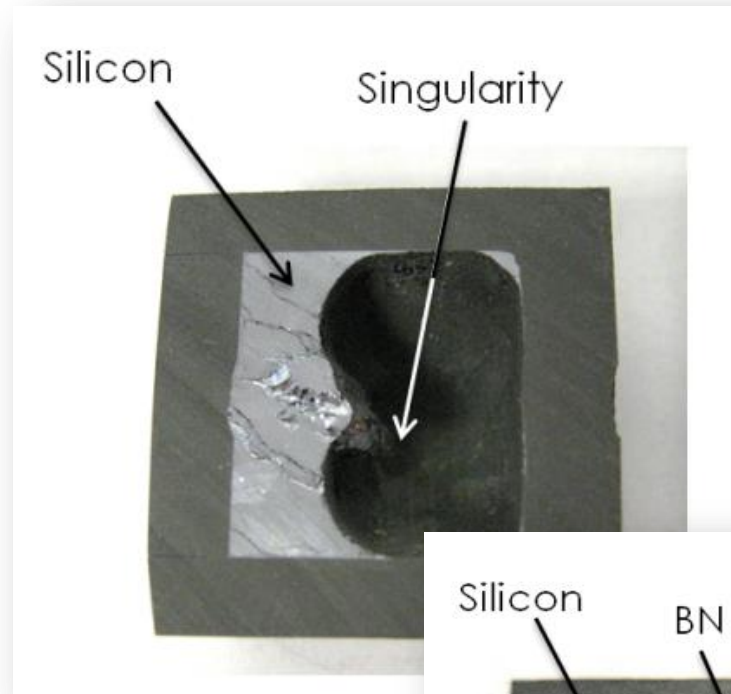


Solar Flux At Best Location

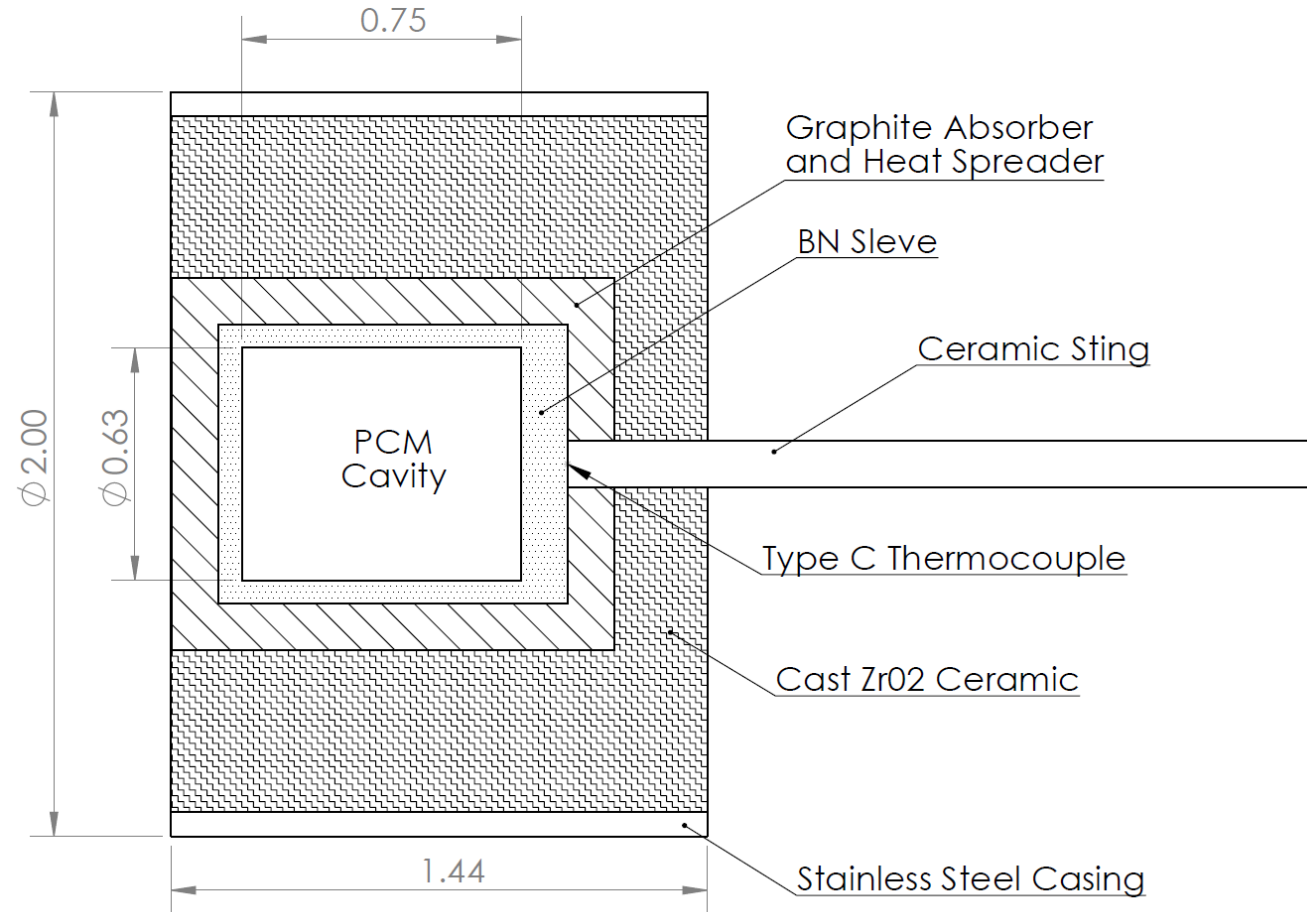
- Peak concentration ratios 4000:1
- Tailored for maximum power delivery in a 1" diameter spot
- Optimized experimental placement using CCD solar flux mapping to compensate for spherical aberrations

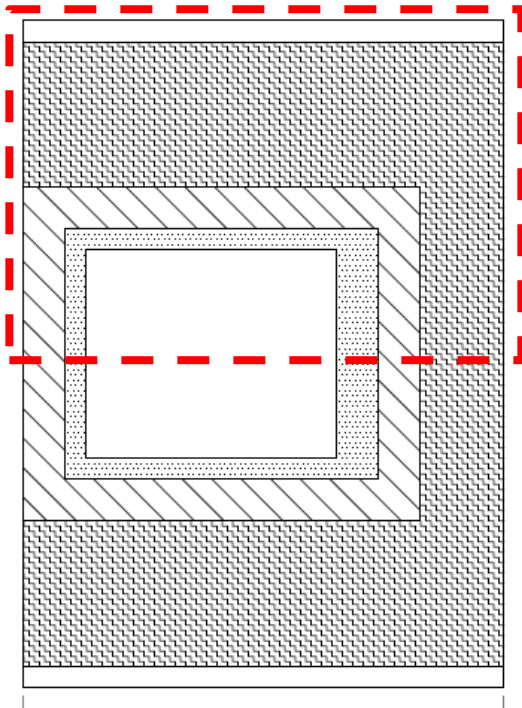


- Possible to draw from semi-conductor industry knowledge
- **Boron nitride** has a self limiting reaction with molten silicon (*also compatible with liquid boron*)
 - Formation of Si_3N_4 limited at 2% boron saturation in the silicon bulk
 - Low level boron contamination expected to have little effect on silicon recrystallization
- Graphite can be used with carbon contamination on the order of 20 ppm
 - Density must be $> 1.75 \text{ g/cc}$
 - Grain size must be $< 50 \mu\text{m}$

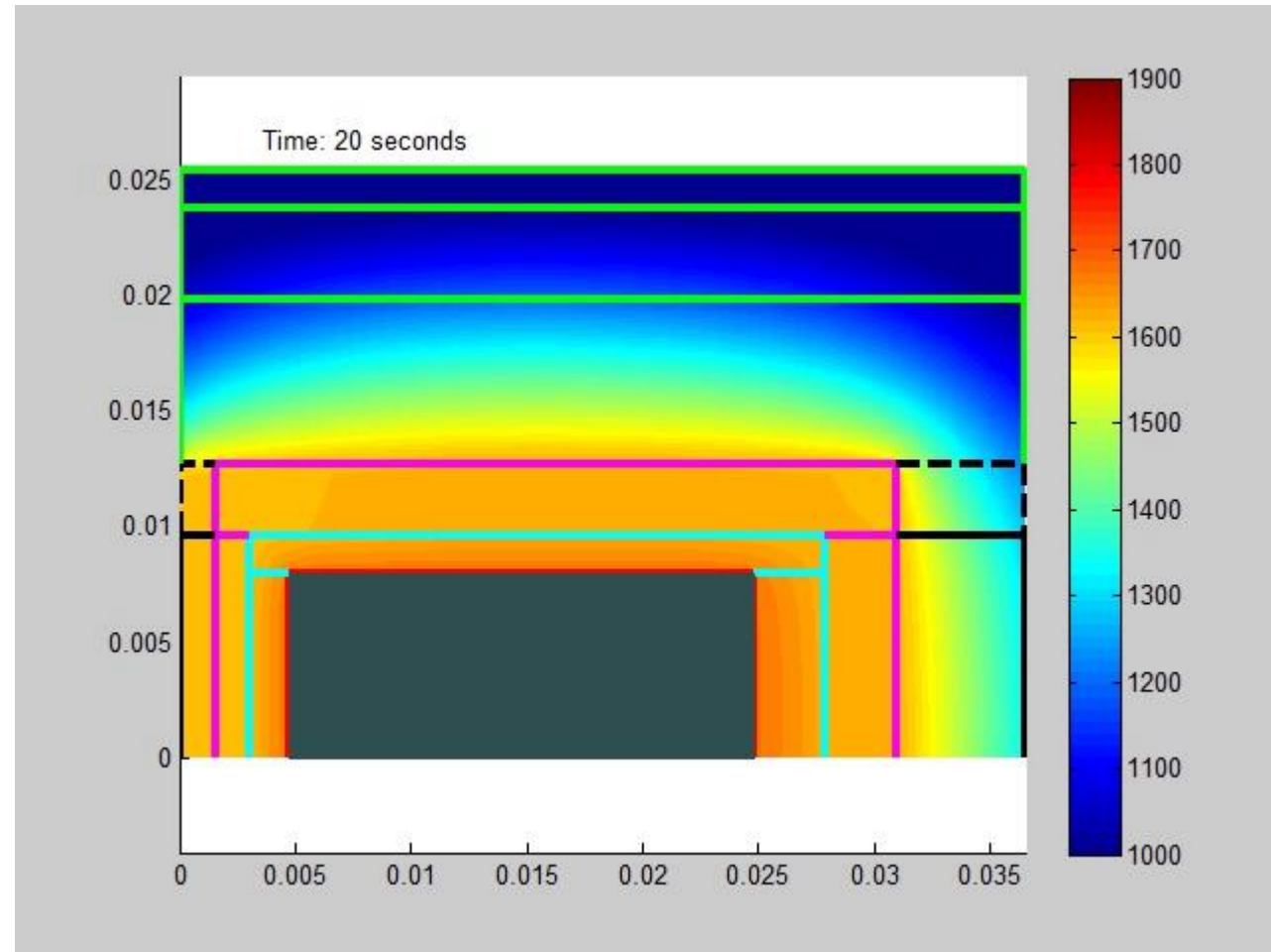


- Cylindrical geometry for ease of manufacture and simplified modeling
- Can be manufactured in house from COTS components
- Sized for 9 g of silicon, however, this is not limited by solar furnace power
- Does not make use of radiation shielding
- Integrated Type C and Type K thermocouples

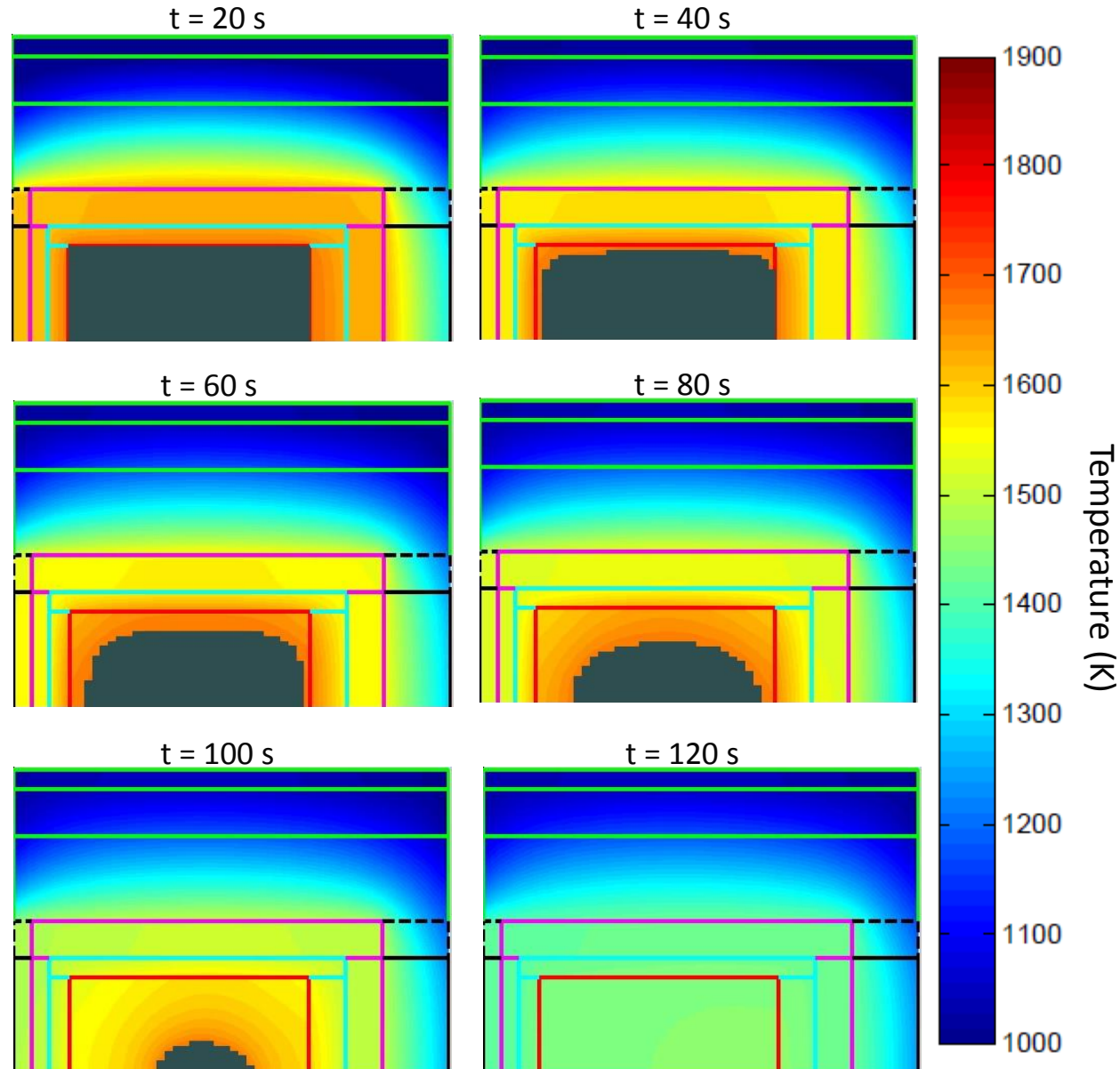
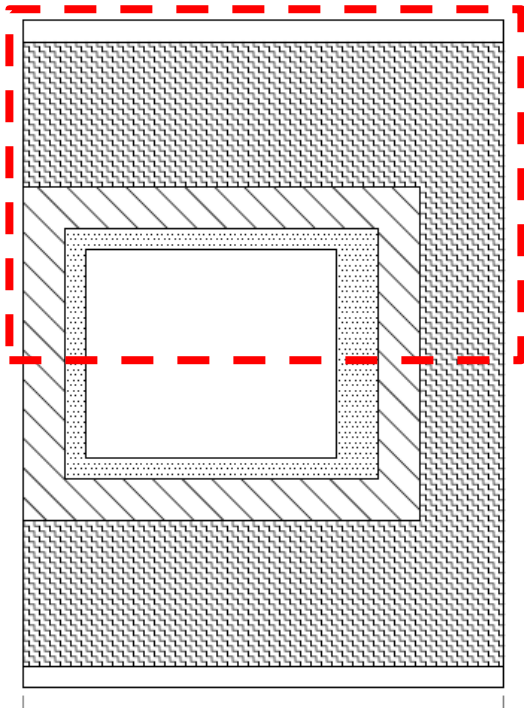




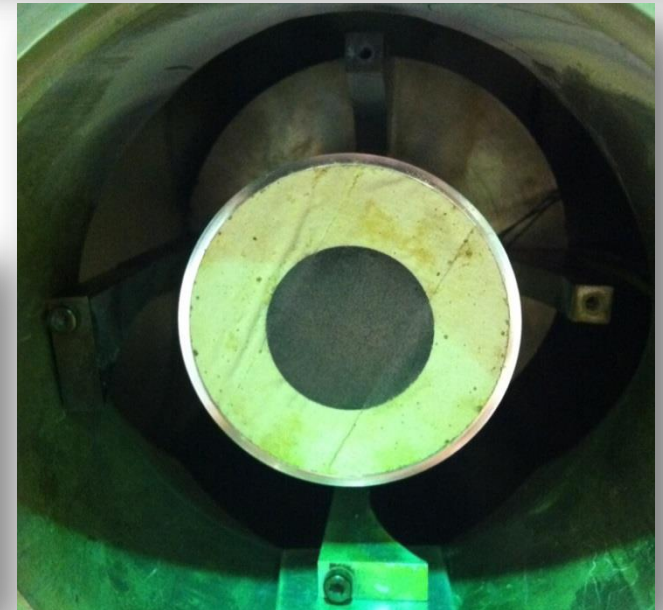
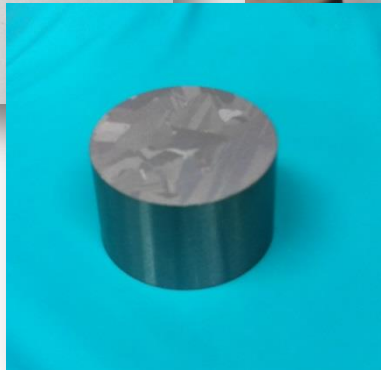
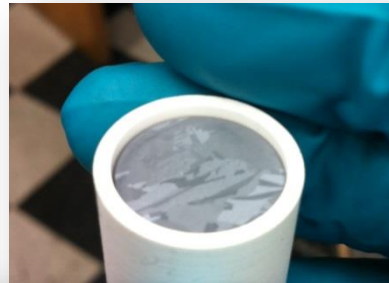
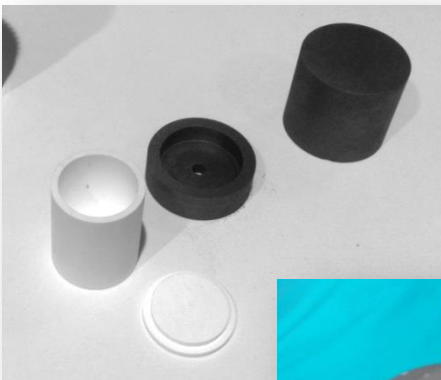
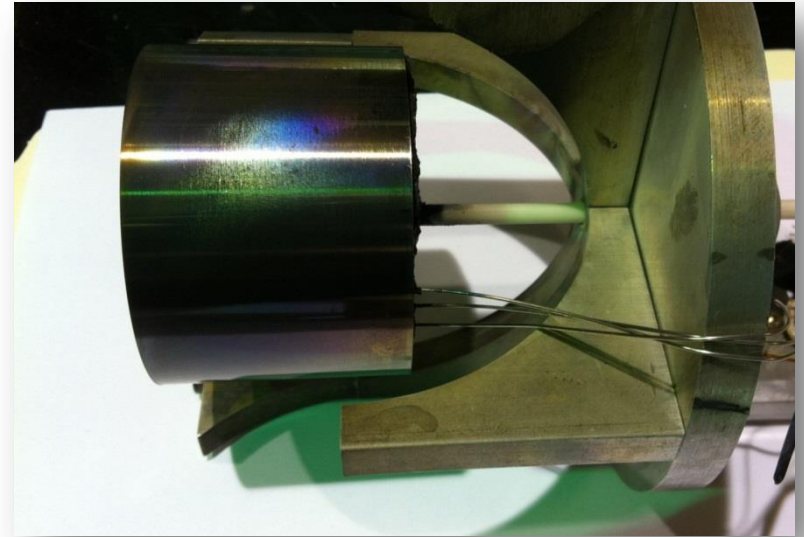
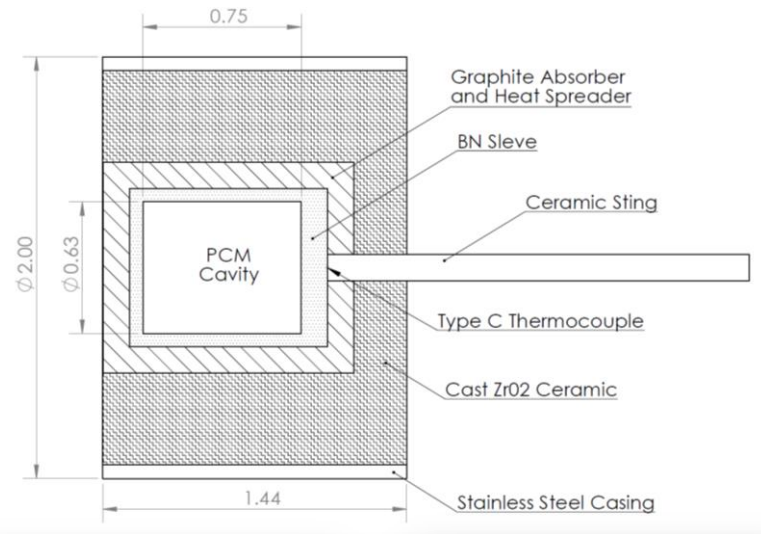
****Movie File to Be Added Here****



- 2D Axisymmetric about θ
- Radiation and convection boundary conditions
- Neglects PCM density change and void formation
- Latent heat handled by the "enthalpy method"

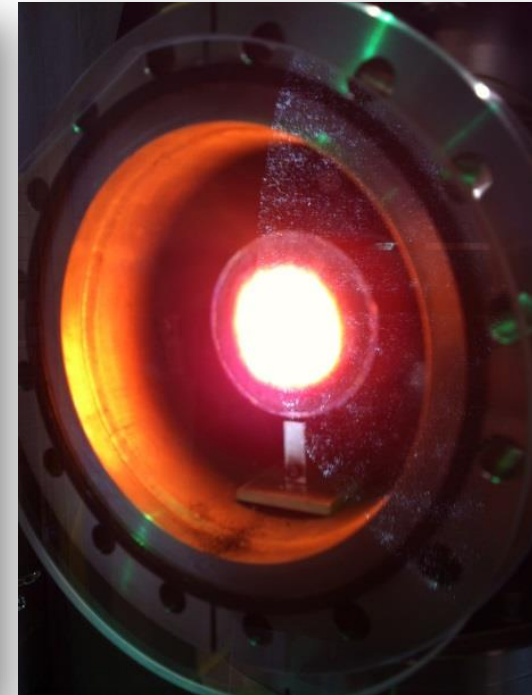


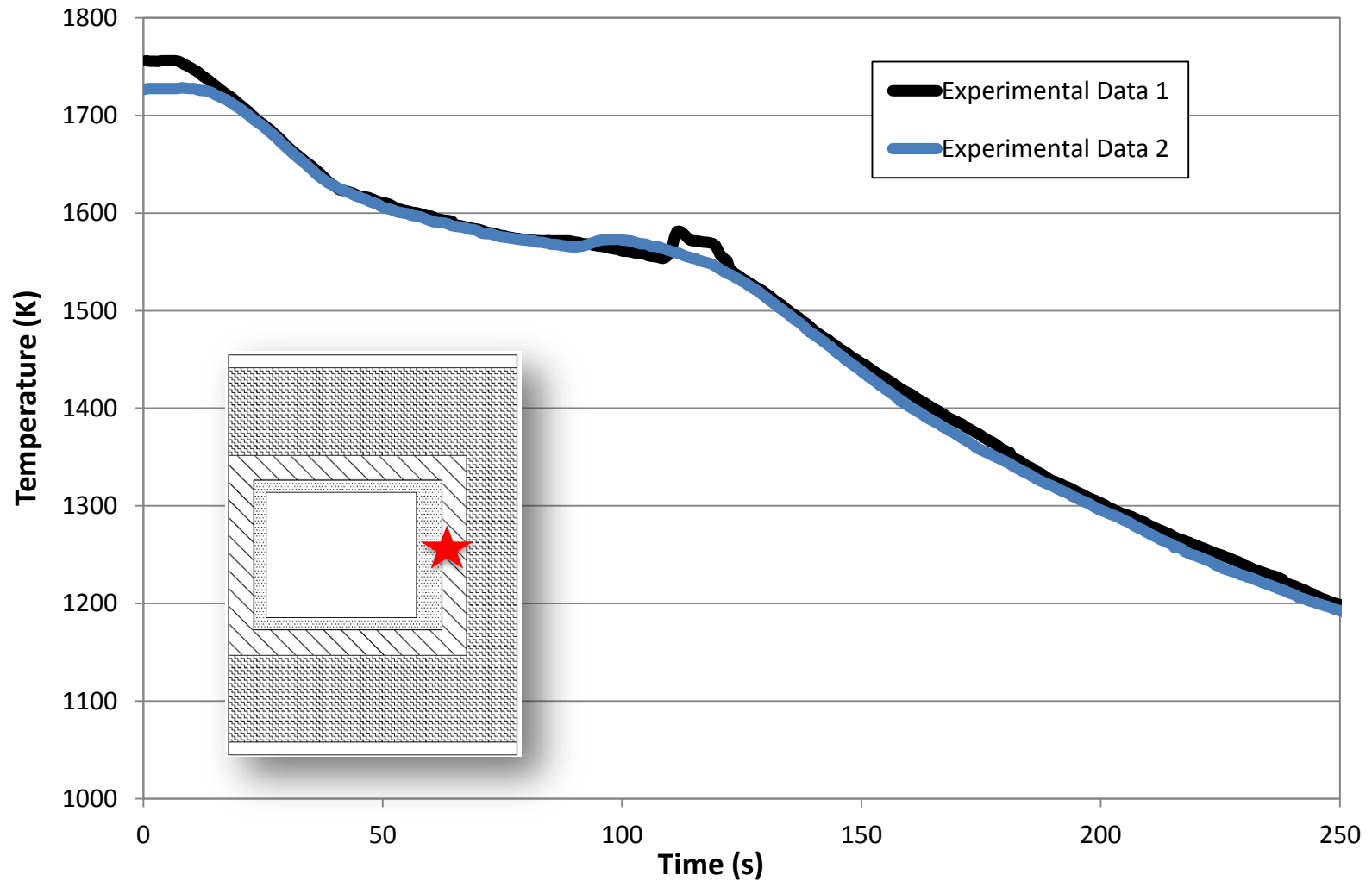
- 2D Axisymmetric about θ
- Radiation and convection boundary conditions
- Neglects PCM density change and void formation
- Latent heat handled by the “enthalpy method”

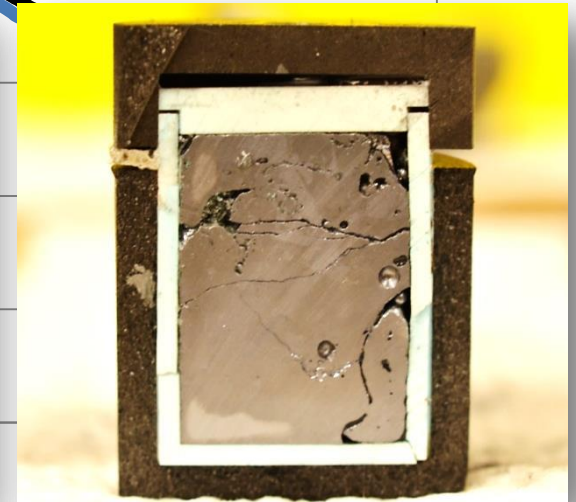
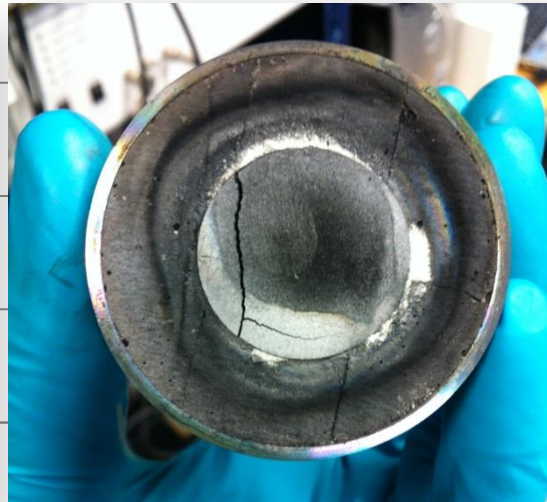
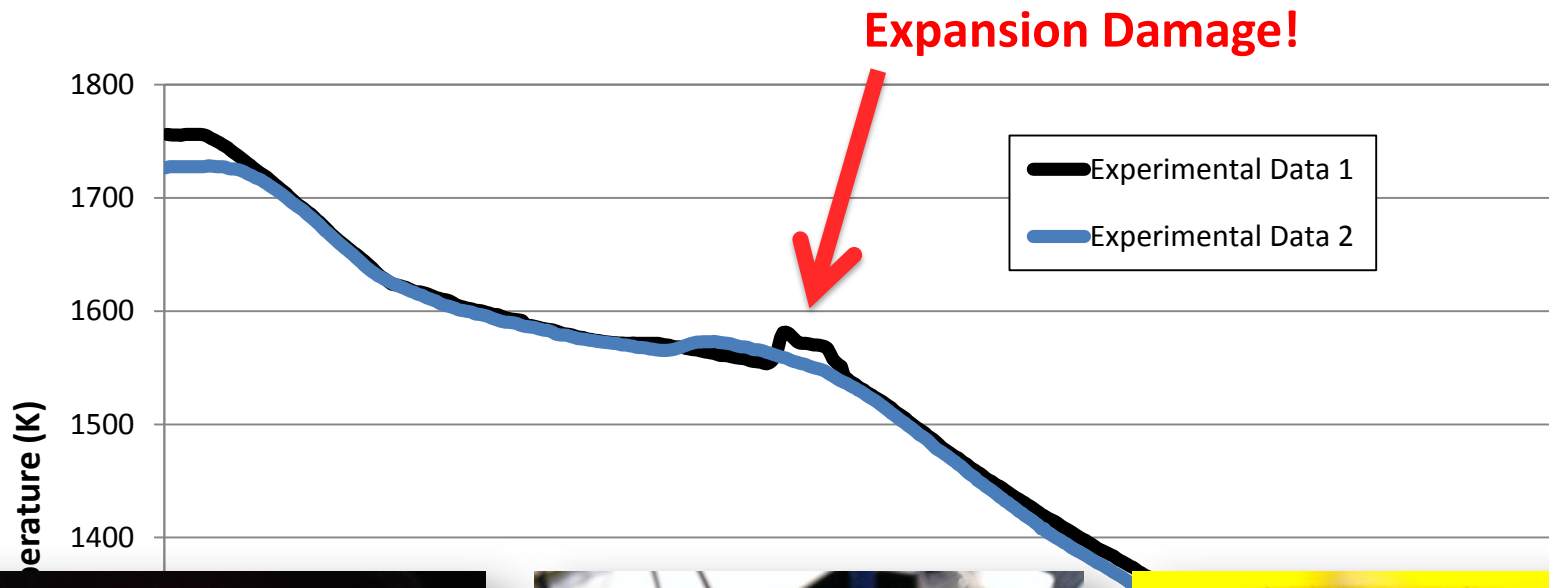


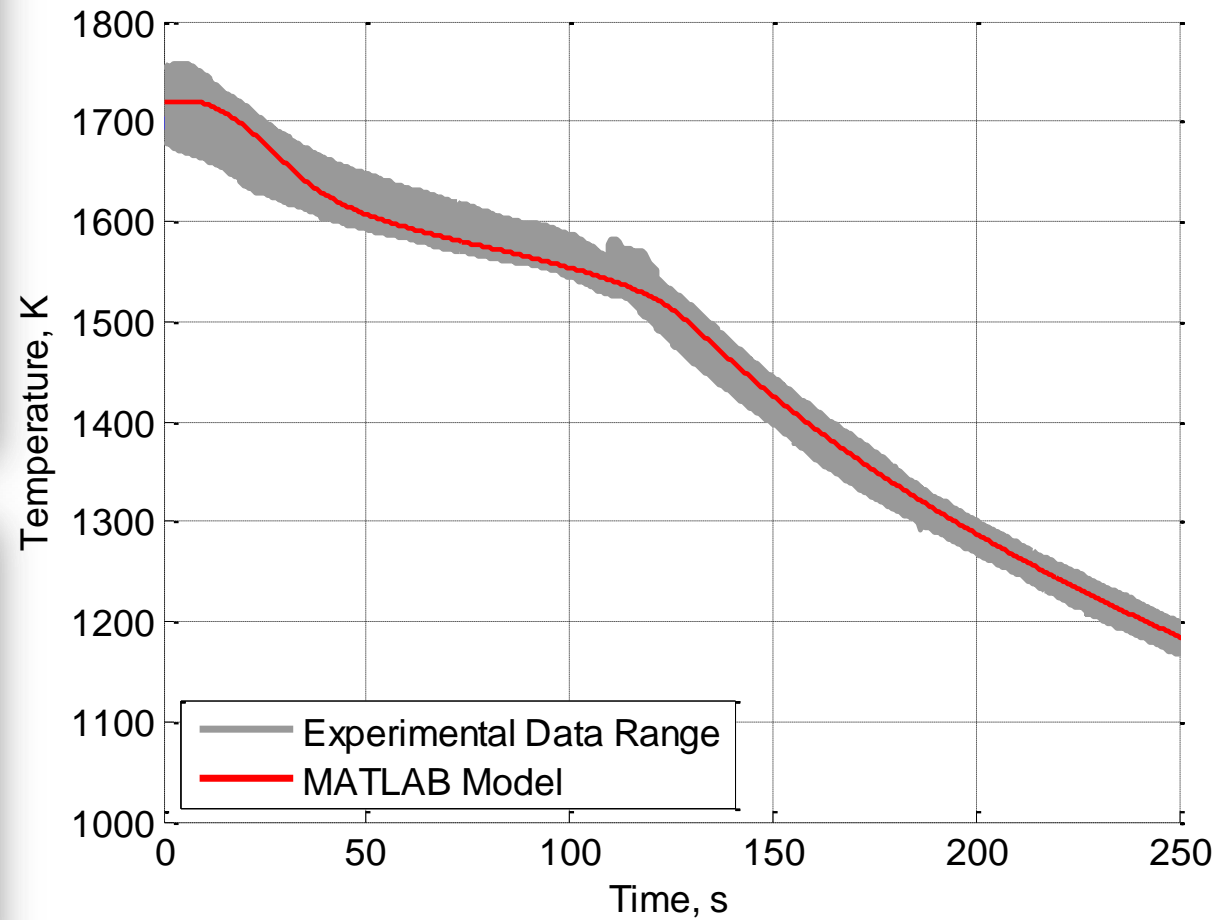
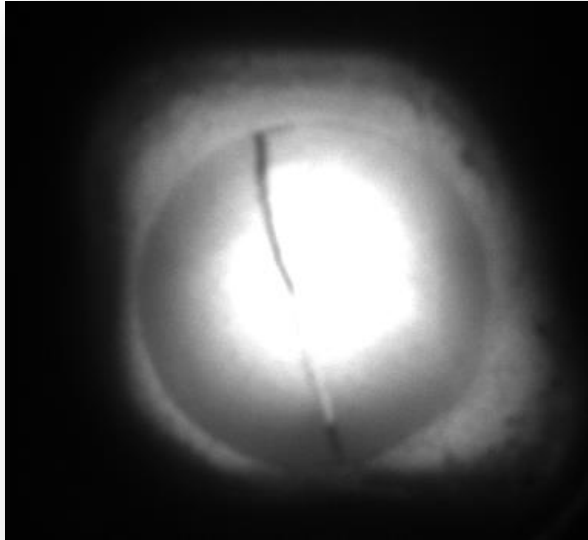
Testing Procedure

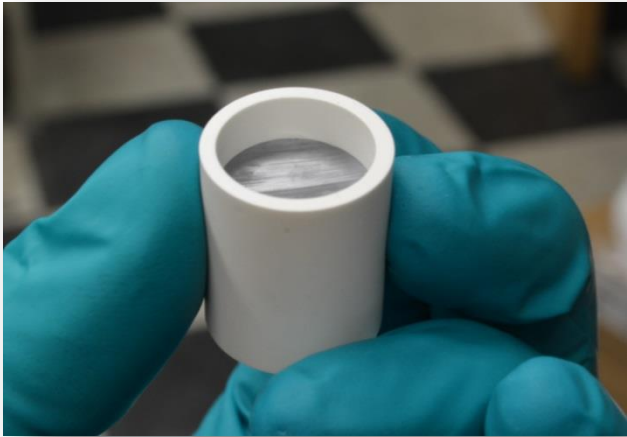
- Bake out at 300 °C and 30 mTorr to evaporate “proprietary water based binder” in the cast ZrO_2 ceramic
- Fill chamber with 150 Torr of Argon
 - Required to suppress $\text{ZrO}_2 + \text{C}$ reaction
 - Prevents irreparable damage to quartz chamber window
- Gradually increase power until thermal equilibrium is achieved
- Use “shutter curtain” to quickly cut power and record cooling curve



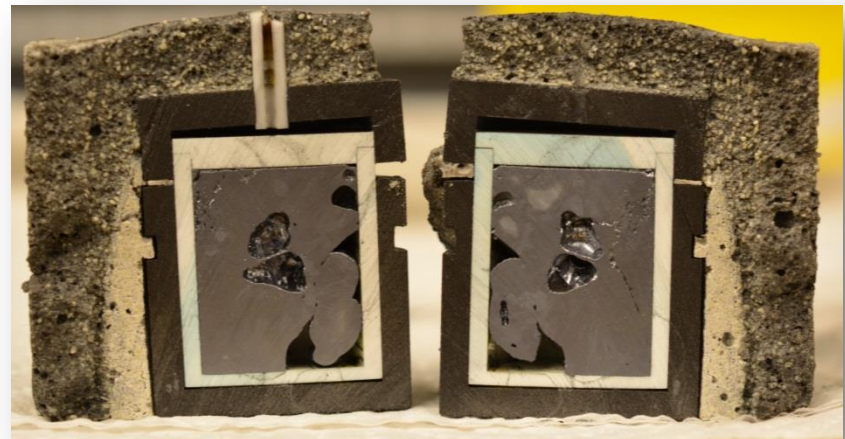
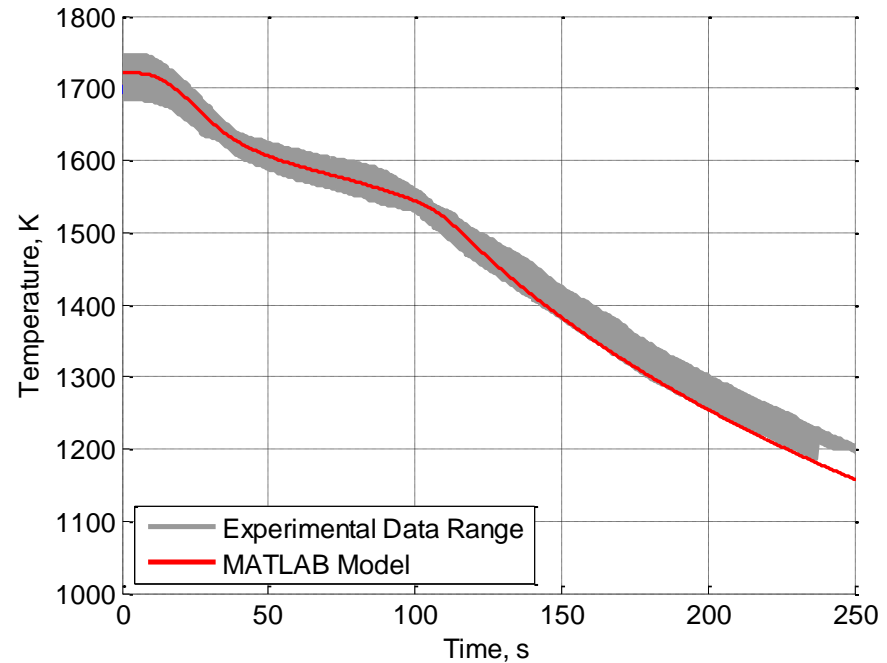


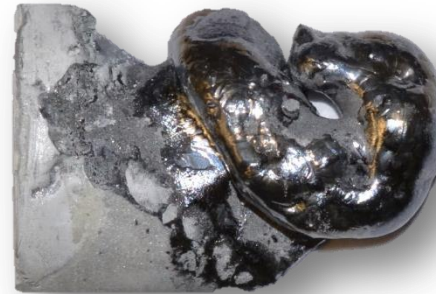


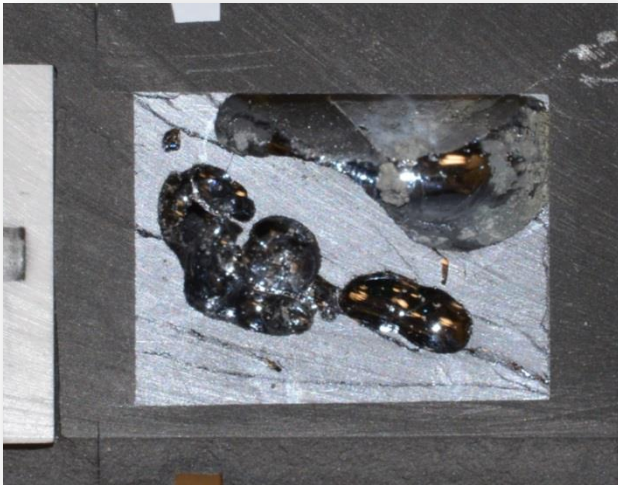




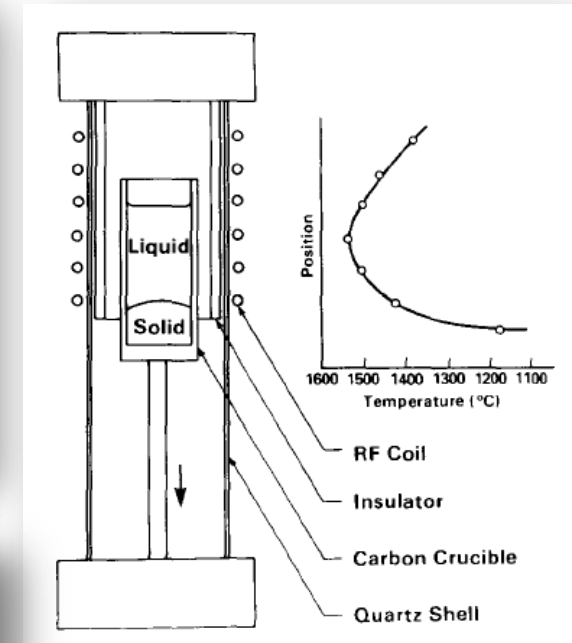
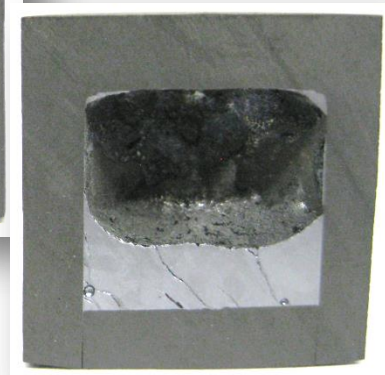
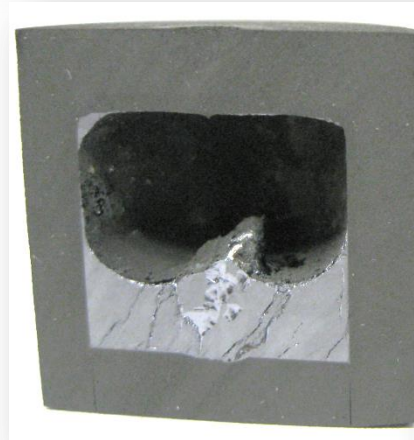
- Successful early tests using silicon powder and chips achieved “fill factors” of approximately 60%
- Tests were performed reducing fill factor from 100% to 80% in 5 % increments
- Audible cracking provided an indication damage during freezing
- No tests < 100% showed macro scale damage. However, all sections showed damage to the inner BN liner



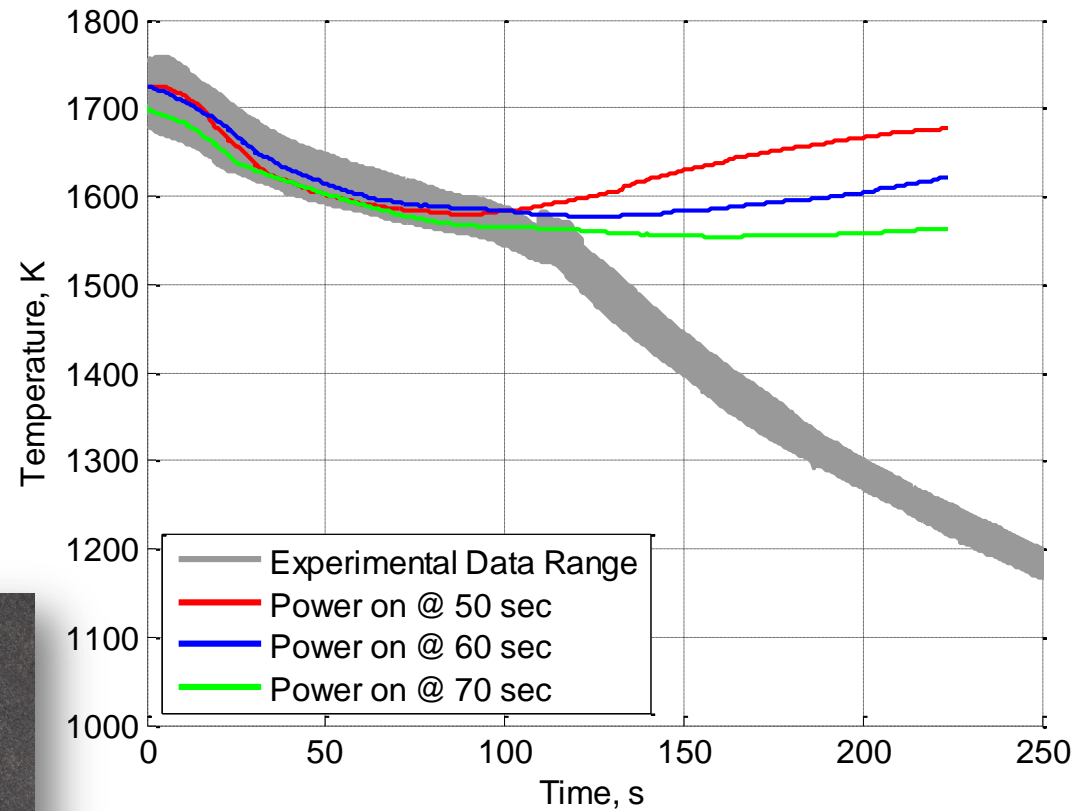




- Production of large silicon ingots precisely controls the phase front
- Graphite crucibles are used with contamination on the order of 20 ppm
- Graphite must be $> 1.75 \text{ g/cc}$ with a grain size $< 50 \mu\text{m}$
- Benefits from wetting behavior?

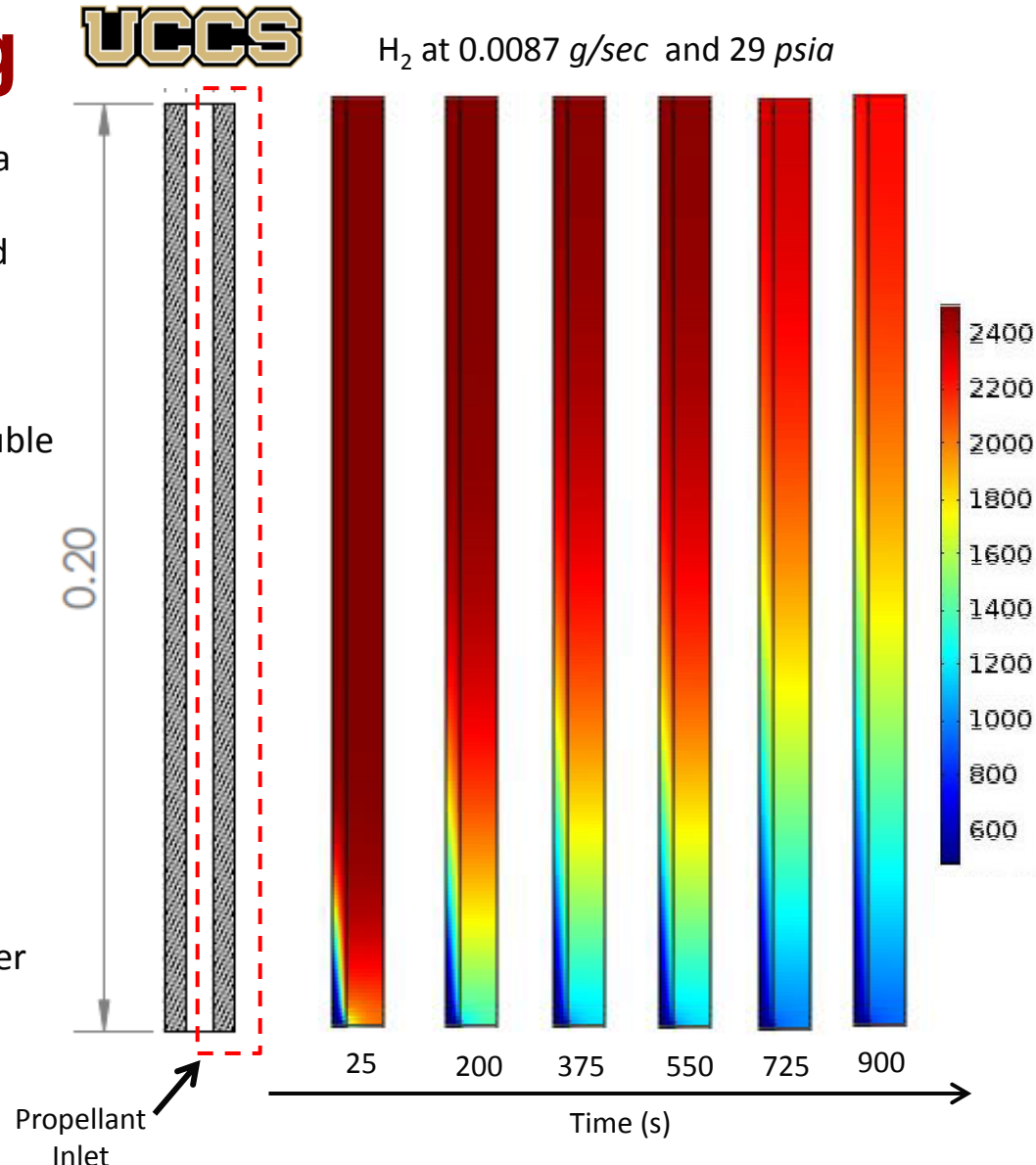


- Only allow silicon to partially freeze?
- Experimentally problematic due to assured failure at the end of testing
- Duty cycle must be matched to eclipse period and power available must consider thermal inertia



Convective Coupling

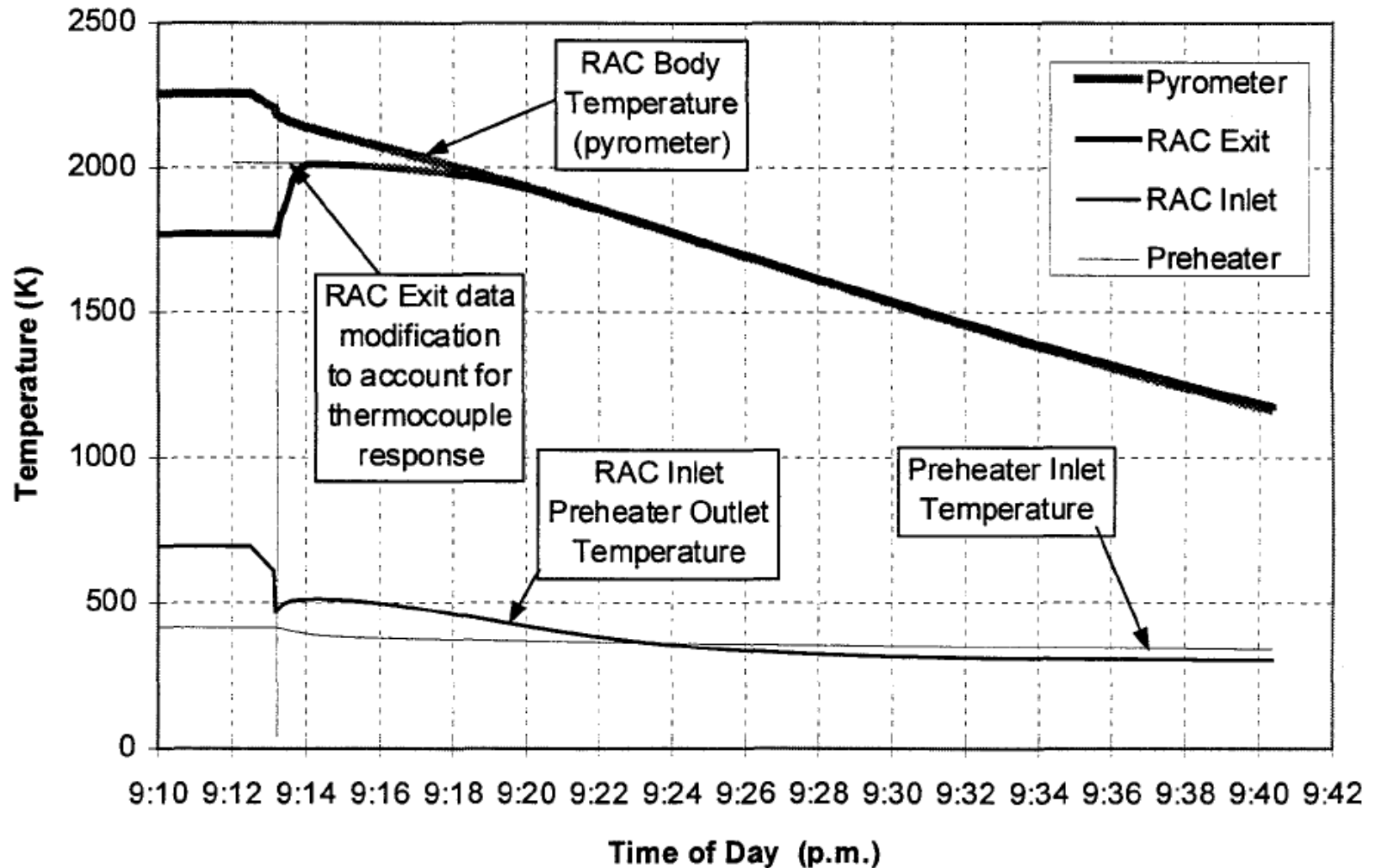
- The ISUS system was capable of maintaining a constant temperature with a sensible heat medium due to “extra length” being designed into the heat exchanger
- The design spec of the ISUS RAC has the potential for 0.72 MJ/kg with a 600 K ΔT (double the original design spec)
- In reality, achieves 0.46 MJ/kg if the steady output region is considered “usable”
- To date, no discussion of latent heat thermal energy storage discusses **advantageous convective coupling**
- Will use commercial multi-physics software (Star-CCM+) to replicate a ISUS heat exchanger channel and switch storage to latent heat
- Seek a quantification of convective coupling benefit



Convective Coupling

UCCS

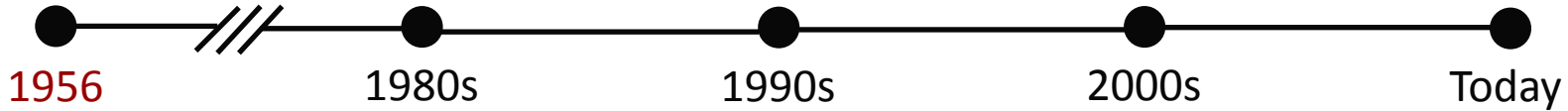
H₂ at 0.0087 g/sec and 29 psia



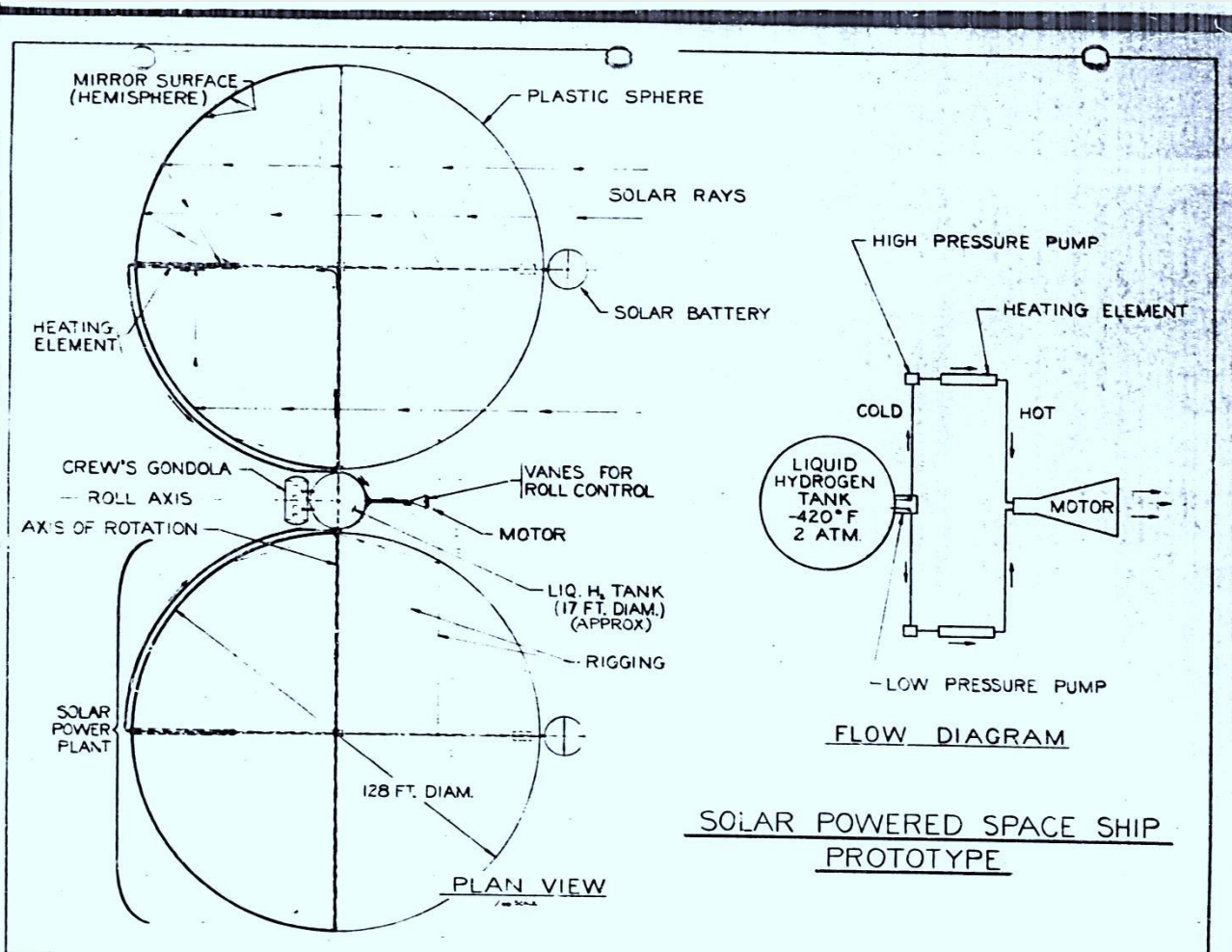


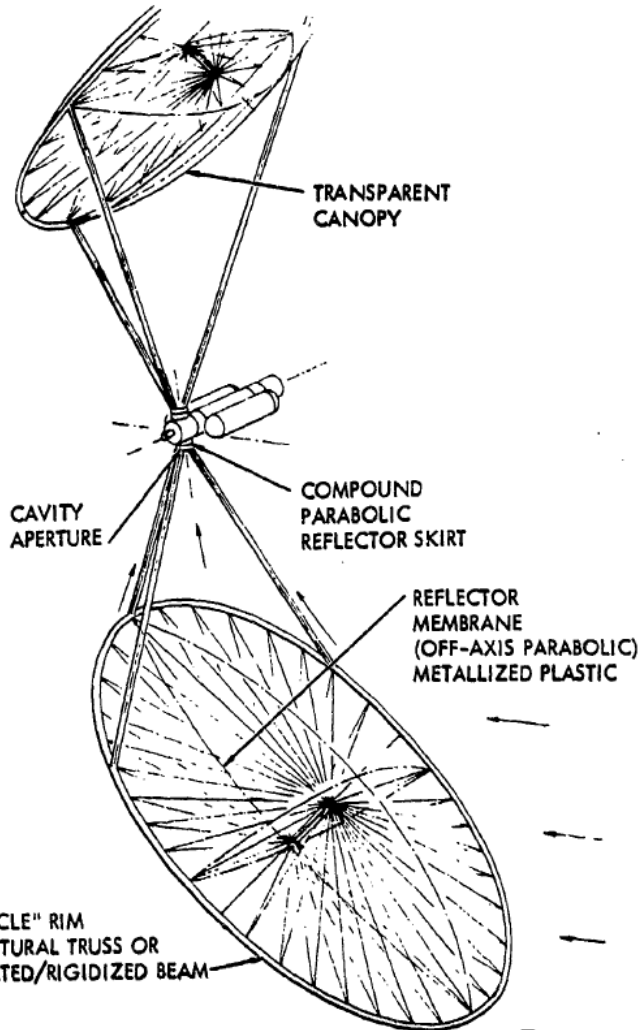
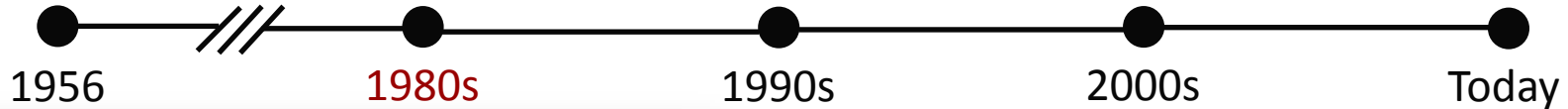
- Bi-modal solar thermal propulsion has the potential to dramatically extend the microsatellite operating envelope
 - $> 1 \text{ km/s } \Delta V$
 - Delivery time measured in *days not years*
- Silicon and boron based thermal energy storage have been frequently mentioned in the literature but lack development due to schedule and funding constraints
- When complete, experiments will bring latent heat thermal energy storage for STP to a similar TRL level as sensible heat options
 - *Volumetric expansion?*
 - *Convective coupling?*
- Thorough experimental investigation into high temperature latent heat thermal energy storage will provide a road map for future solar thermal system designers





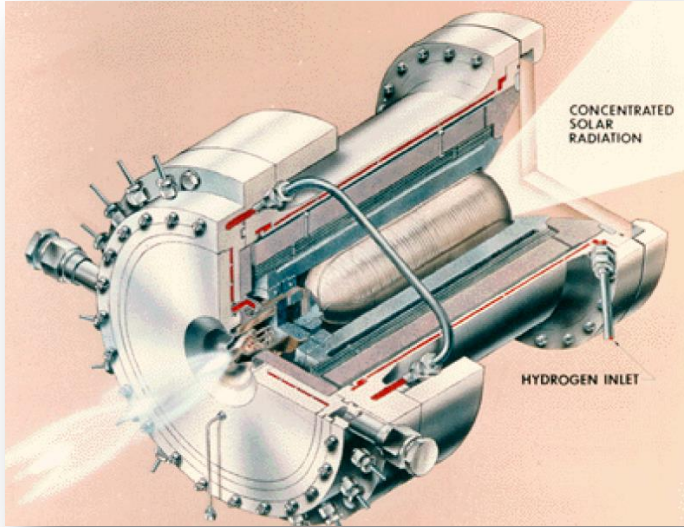
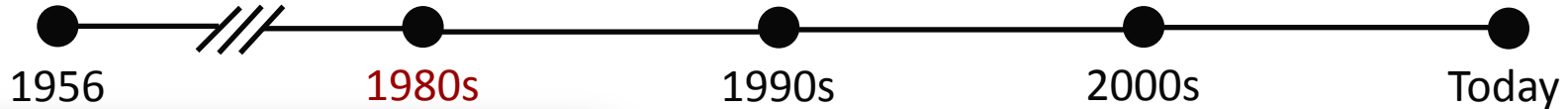
- “Solar Powered Space Ship” proposed by Krafft Ehricke
- 7500 kg spacecraft with a two man crew
- AFRPL funded investigation at Electro-Optical Systems (EOS) in 1963 produced solar heated H_2 at approx. 2300 K
- Work halted due to concerns about “awkward” vehicle design and integration issues
- Funding was shifted to a competing advanced concept





- Space Shuttle – “represents a national commitment to extended operations in space” *Selph 1981*
- 1979 Rockwell report, funded through AFRPL, concludes a solar thermal rocket is possible and recommends near term production
- Vehicle integration was greatly simplified by a centrally located solar receiver and inflatable concentrators
- Compared performance of **28,100 kg**, shuttle launched spacecraft for LEO-GEO transfer

Engine Type	LO ₂ H ₂	Ion	Solar 1	Solar 2
ΔV (m/s)	4,270	5,850	5,850	4,800
Isp (sec)	475	2,940	872	872
Trip Time (days)	5	180	14	40
Payload to Geo (kg)	9,250	20,000	9,300	13,200



- AFRPL funded effort for experimental demonstration based on findings of Rockwell report
- Rocketdyne contracted to produce a solar thermal thruster using coiled rhenium tubing with a target exit temperature of 2705 K
- Solar furnace problems limited testing temperatures to approximately 1800 K
- AFRPL declared technology “feasible” but development was slowed in 1989 due to budget cut-backs
- Note that the design **does not** include a means of thermal energy storage

“...time spent traversing the Earth shadow results in a trip-time increase of approximately 10% at no increase in propellant expended.”

Ethridge 1979



- A **bi-modal** nuclear thermal system capable of providing propulsive and electrical power was proposed in the early 1990s
- Integrated upper stage design supplies electrical power to the payload after orbit transfer
- Reduced mass: potential for launch vehicle “step down”

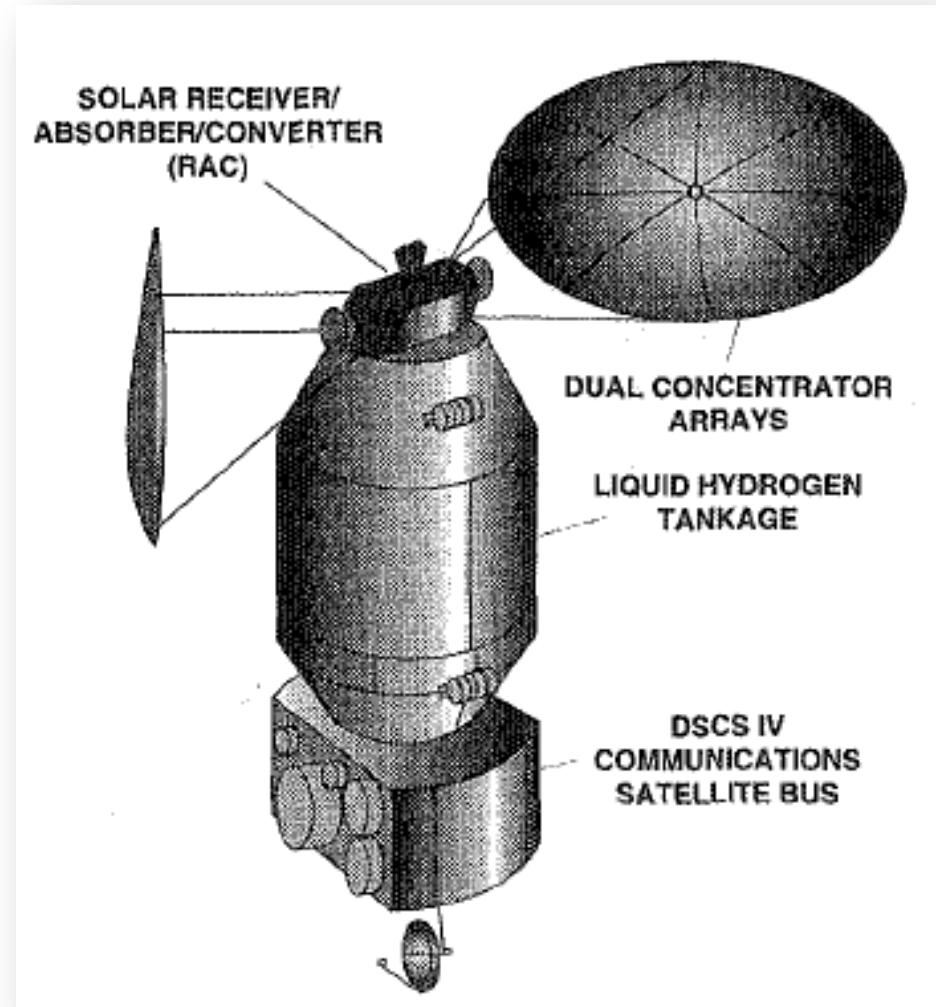
Delta II 7925

\$50M in 1995
1800 kg to GTO

Titan IIG

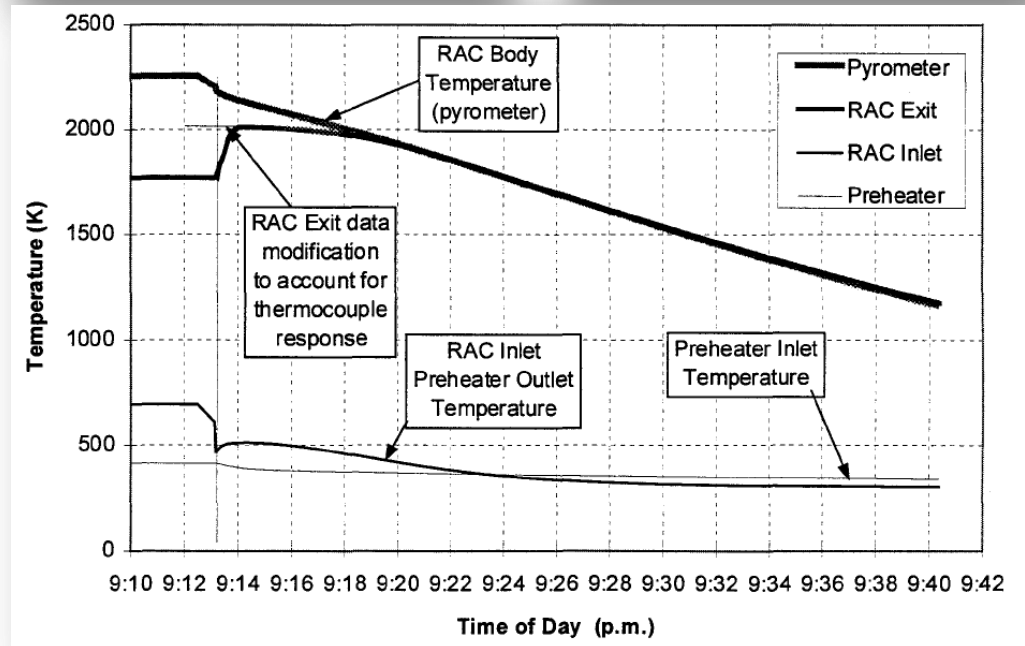
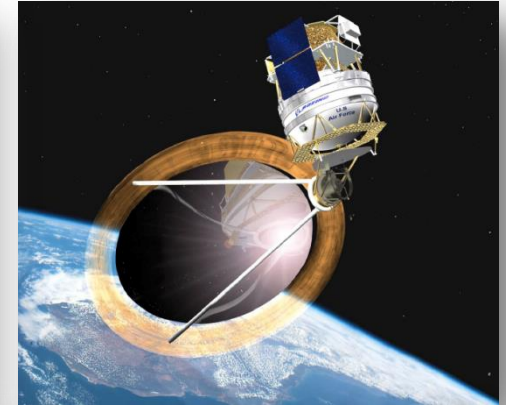
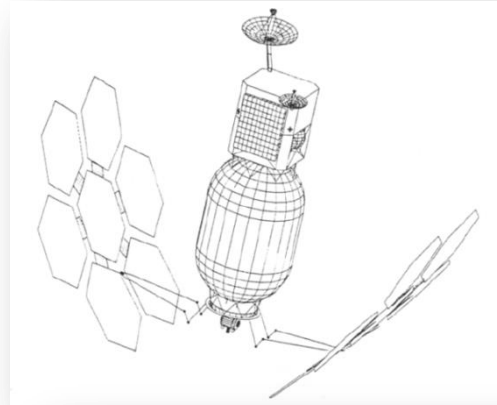
\$18-30M in 1995
1000 kg to GTO

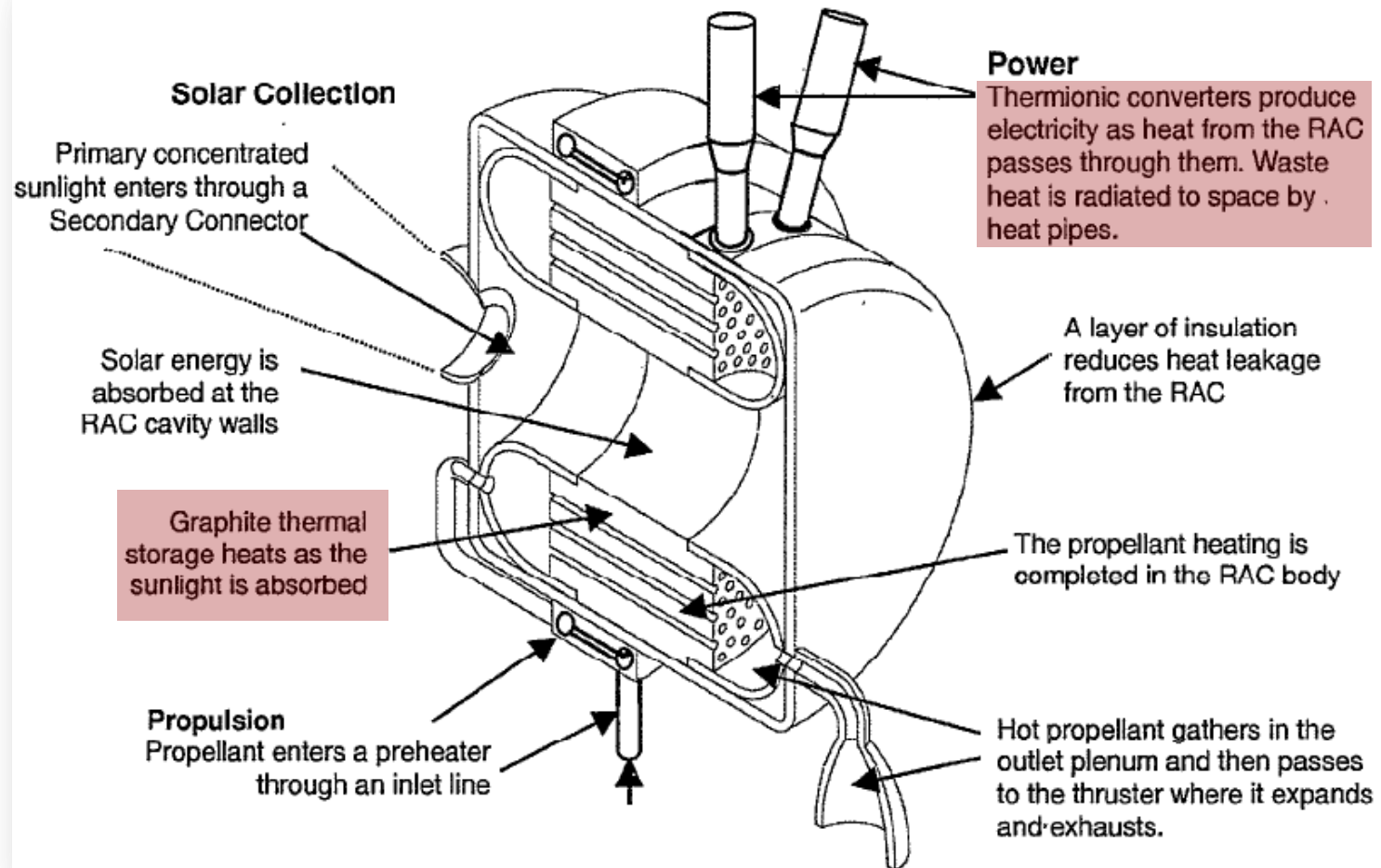
- Due to waning interest in nuclear thermal research, AFRPL considered the concept with a solar thermal architecture
- Sought to quickly reduce the cost of Air Force space operations using *existing* technology

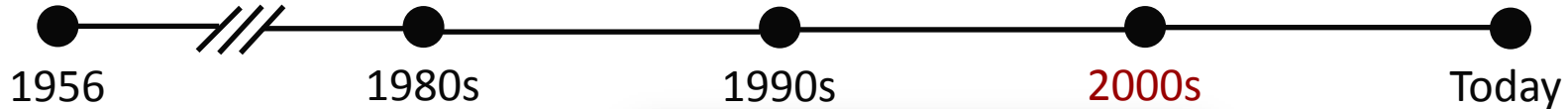




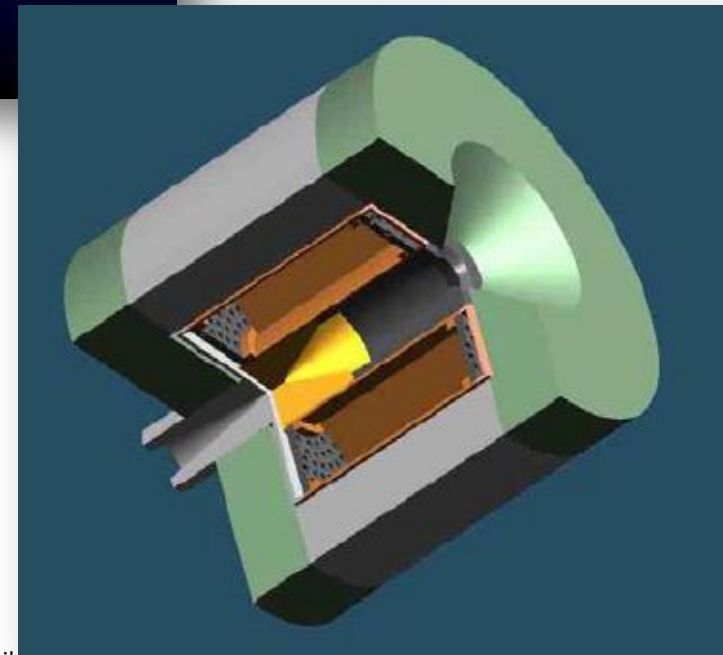
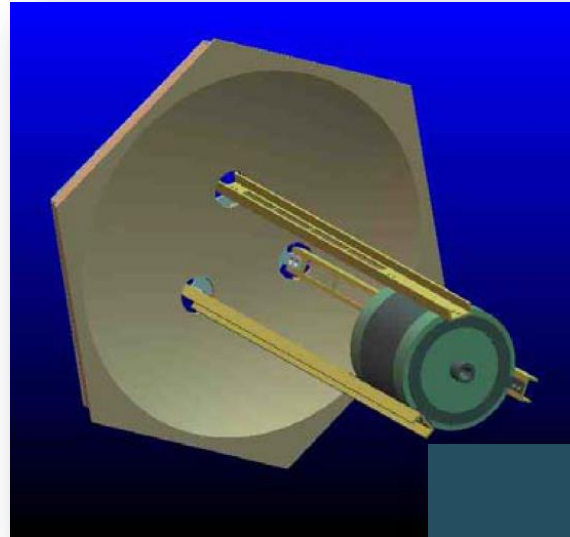
- Integrated Solar Upper Stage Program (ISUS) initiated in 1994
- ISUS program targeted a “militarily” useful payload on orbit by 1998 – *very optimistic*
- Performed a ground test of a prototype Receiver-Absorber-Converter (RAC)
- RAC incorporated sensible heat thermal energy storage – necessitated by the bi-modal design
- Succeeded in recording data for hot flow hydrogen testing
- Program closed in 1998 – followed by Boeing Solar Orbit Transfer Vehicle (SOTV) and the STP Critical Flight Experiment at NASA Marshall

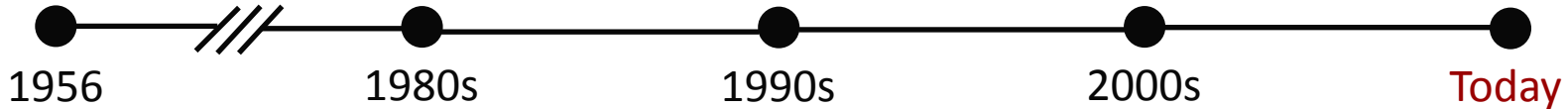




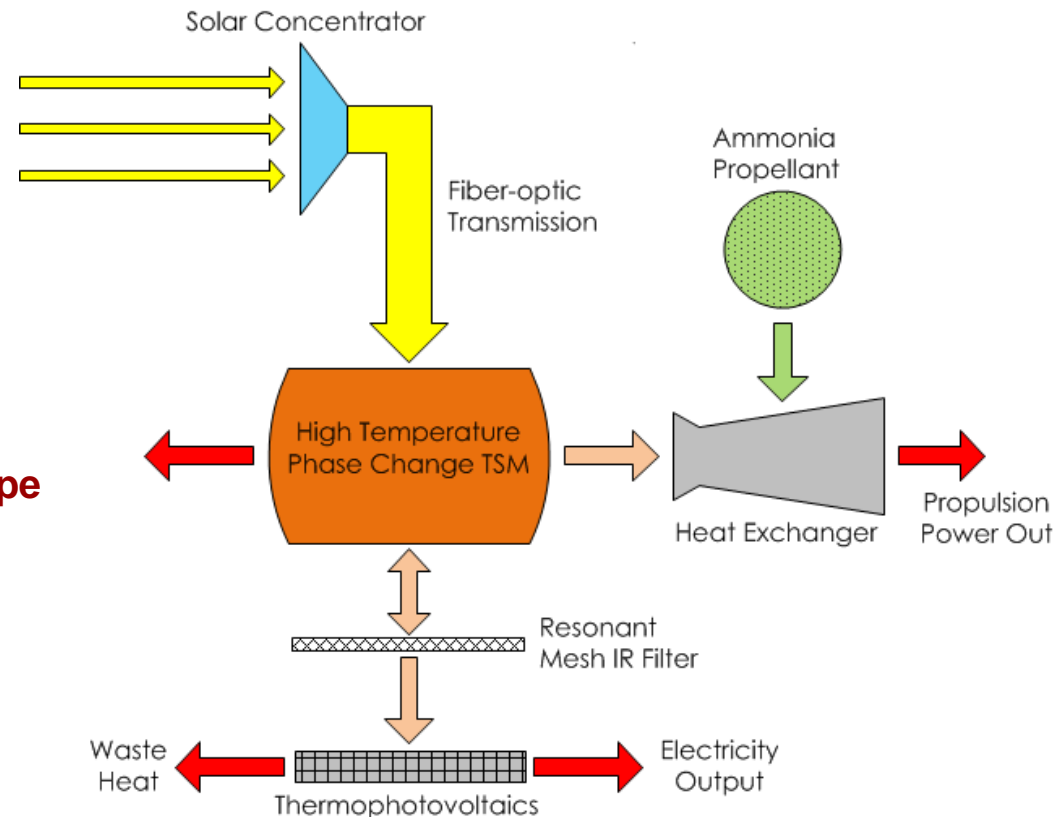


- Concept shifted to microsatellites (10-100 kg) in an effort to *finally* mount a space demonstration
- Project headed by Kennedy, a veteran of the ISUS program, at Surrey Space Center
- Proposed the use of non-cryogenic propellants such as N_2H_4 and NH_3 and “packed bed” sensible heat thermal energy storage
- Achieved experimental NH_3 temperatures approaching 2000 K
- Other small scale research efforts
 - Thin film concentrator and Mo receiver work at JAXA
 - Fiber optic coupling work at Physical Sciences Inc





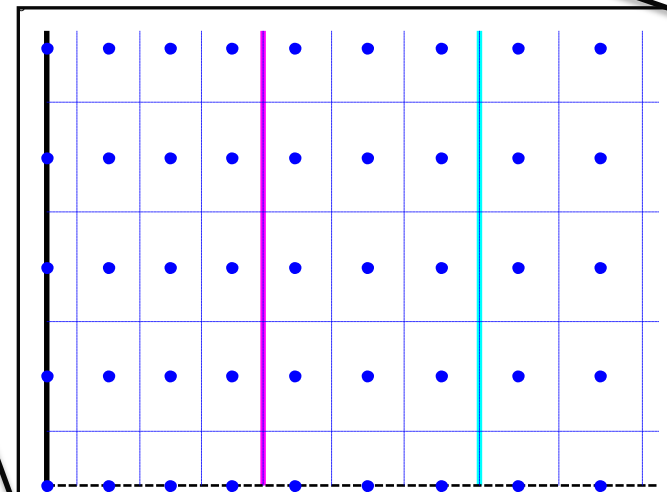
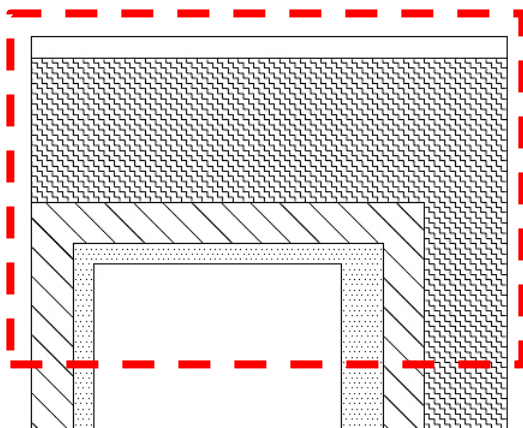
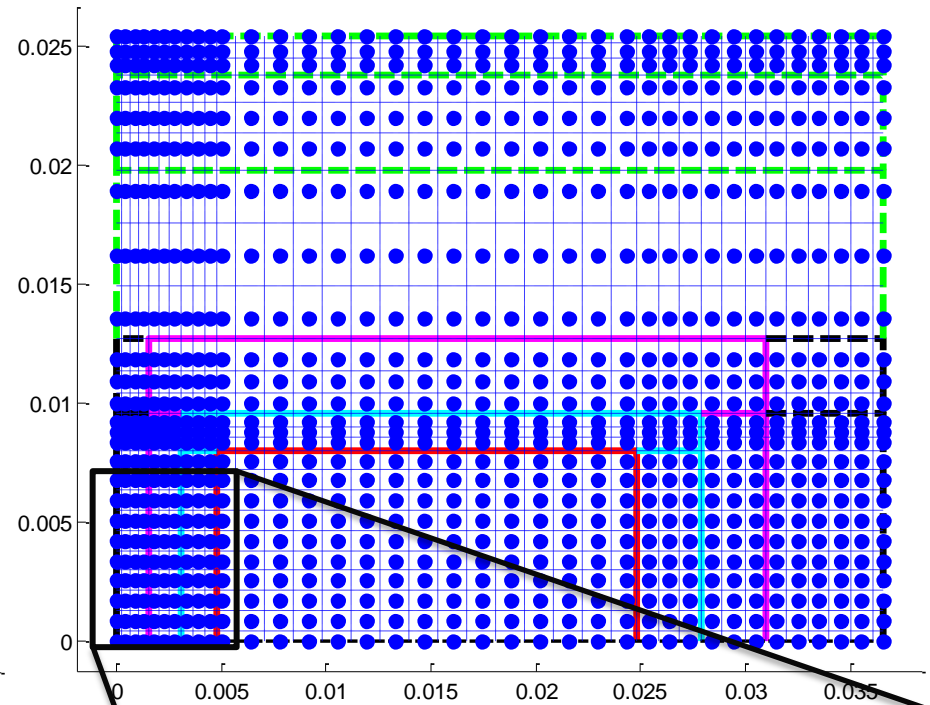
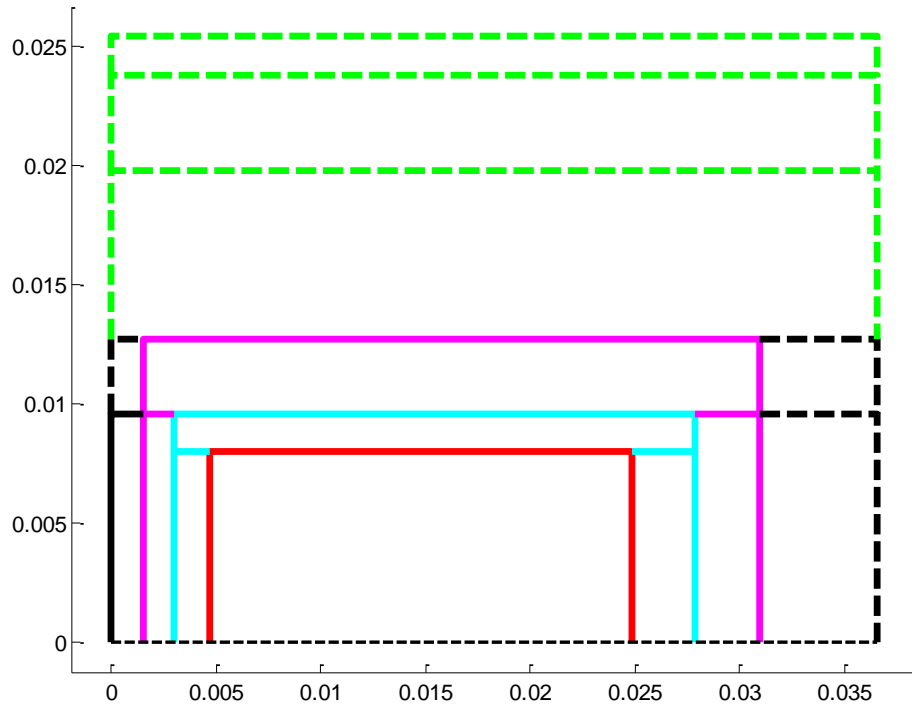
- Drawing from Kennedy's microsatellite study, a review by the AFRPL advanced concepts group identified STP as a promising candidate for high performance microsatellite missions
- A **bi-modal microsatellite** configuration is proposed and further study is recommended
- Microsatellite scaling distinguishes STP
- Large ΔV (> 1 km/s) possible



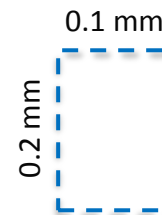
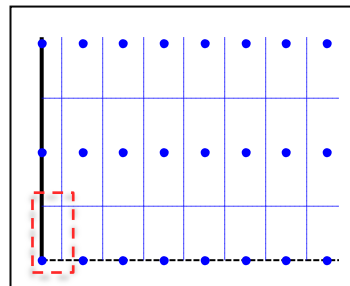
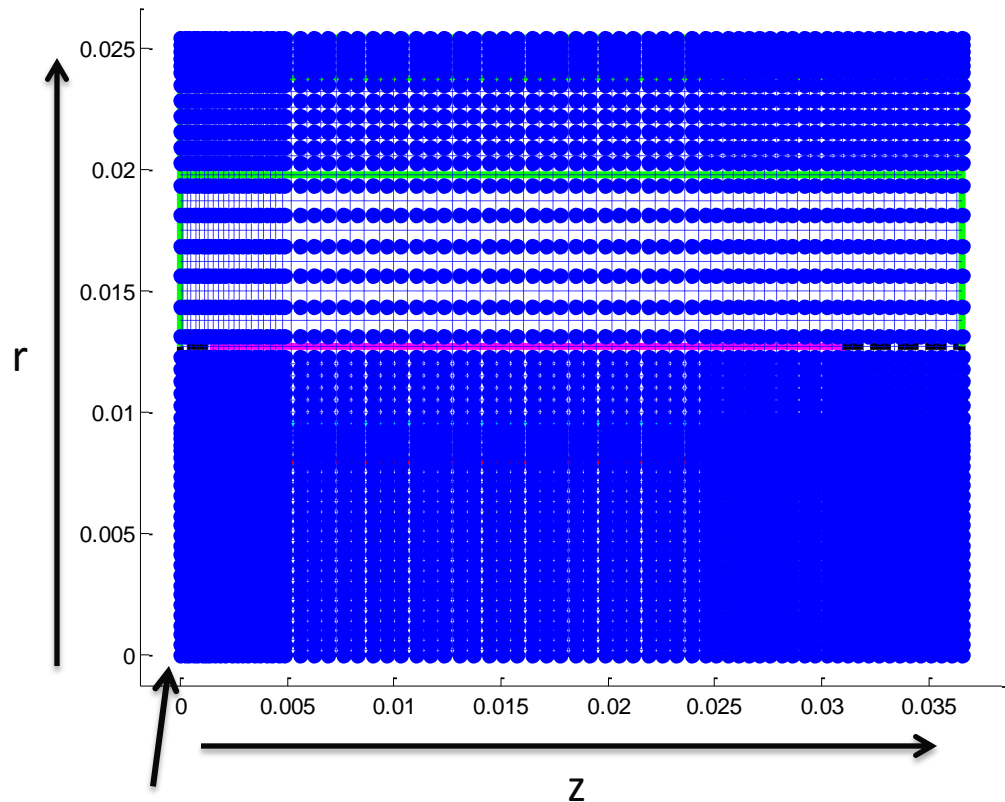
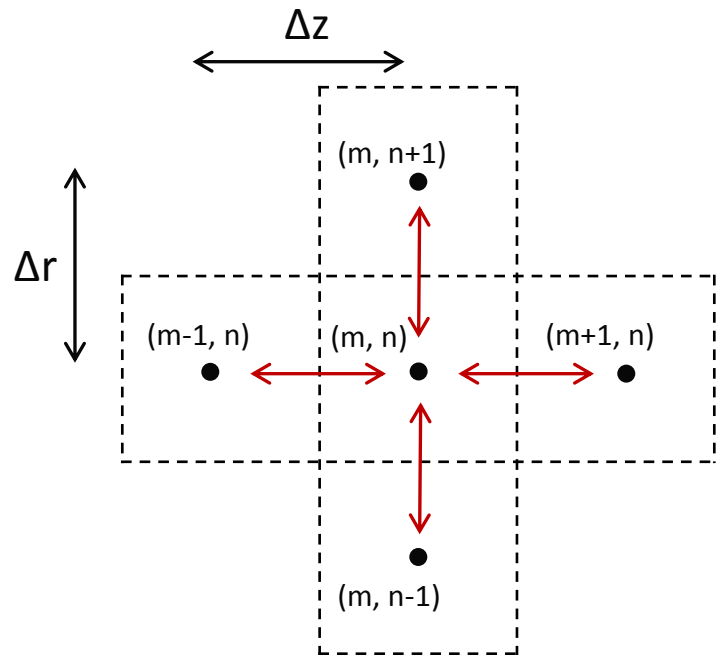
Expand the Microsatellite Operating Envelope

- Expand possible “piggy-back” launch options
- GEO Insertion: ~ 1760 m/s
- Near Escape Missions: $\sim 770 - 1770$ m/s

Possible with EP, however, STP offers a much shorter burn time and higher maneuverability



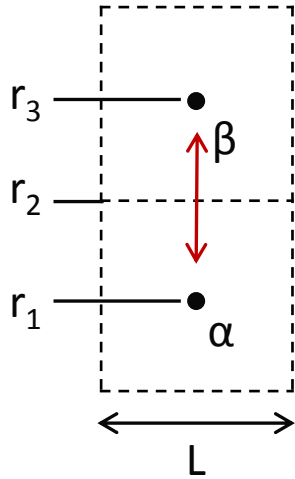
- 3700 Nodes
- $dt = 0.00025$ seconds
- Approx. 14 hours runtime for a 300 second simulation



$$V = 1.3 \times 10^{-5} \text{ cc}$$

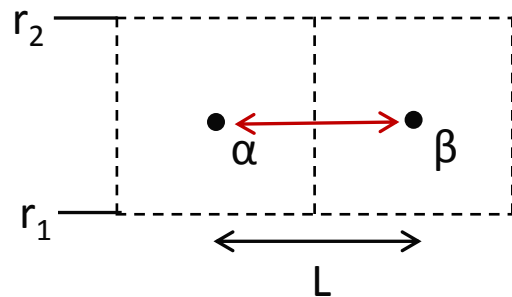
$$m = 2.65 \times 10^{-5} \text{ g}$$

Conduction in the “r” Direction



$$q = \frac{(T_\beta - T_\alpha)}{\frac{\ln(r_2/r_1)}{2\pi L k_\alpha} + \frac{\ln(r_3/r_2)}{2\pi L k_\beta}}$$

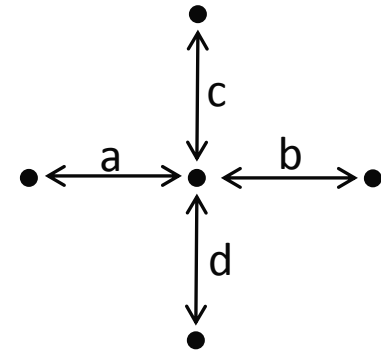
Conduction in the “z” Direction



$$q = \frac{A(T_\beta - T_\alpha)}{L(1/k_\alpha + 1/k_\beta)}$$

$$A = \pi(r_2^2 - r_1^2)$$

All geometric terms are offloaded into coefficient matrices to speed computations



At Each Time Step

$$q_{net} = q_{left} + q_{right} + q_{down} + q_{up}$$

$$\Delta T = \frac{q_{net} dt}{mc_p}$$

Node With PCM

$$\Delta T = \frac{q_{net} dt}{mc_p} + LatentHeat(rr, zz)$$

Radiation Boundary Condition

$$q_{rad} = -\sigma \epsilon A (T_{node}^4 - T_{amb}^4)$$

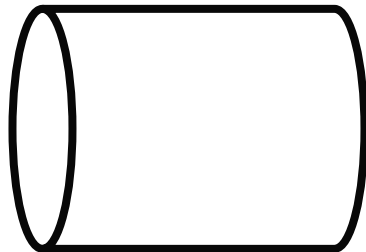
$$q_{net} = q_{left} + q_{right} + q_{down} + q_{up} + q_{rad} + q_{conv}$$

$$\Delta T = \frac{q_{net} dt}{mc_p}$$

Convective Boundary Condition

$$q_{conv} = -hA(T_{node} - T_{amb})$$

Assume Long
Horizontal Cylinder



Assume
Vertical Plate

Vertical Plate $\rightarrow h \approx 6.7 \text{ (W/m}^2\text{K)}$

$$h = \frac{k}{L} \left(0.825 + \frac{0.387 Ra_L^{1/6}}{(1 + (0.492/Pr)^{9/16})^{8/27}} \right)^2 \quad (\text{Churchill and Chu})$$

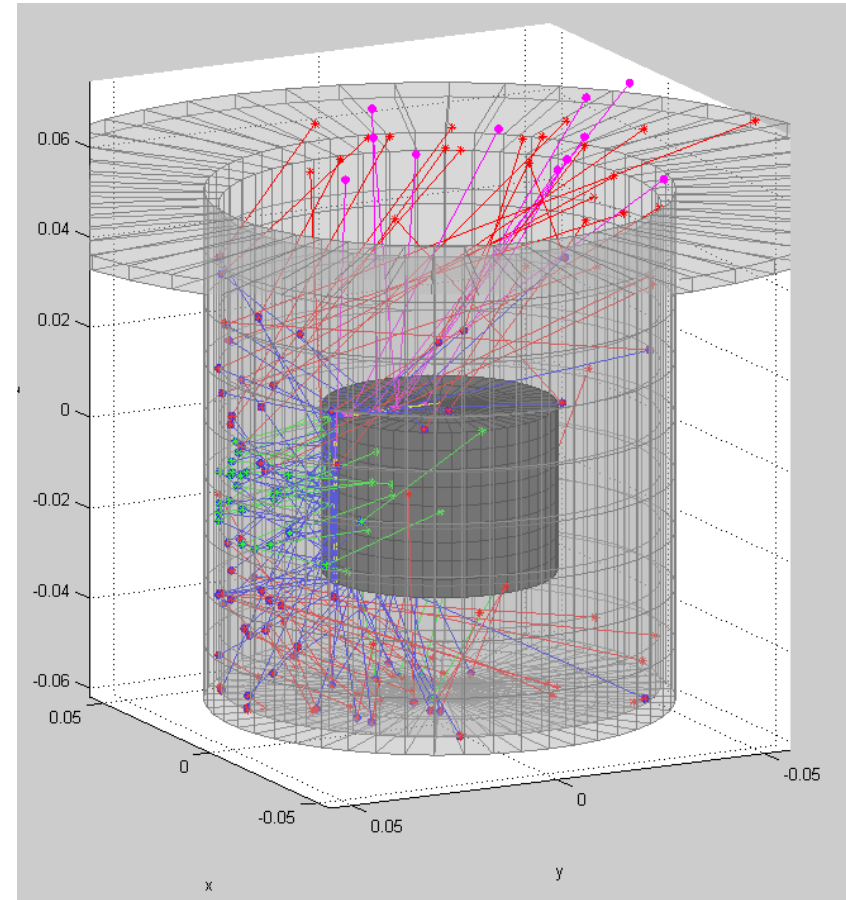
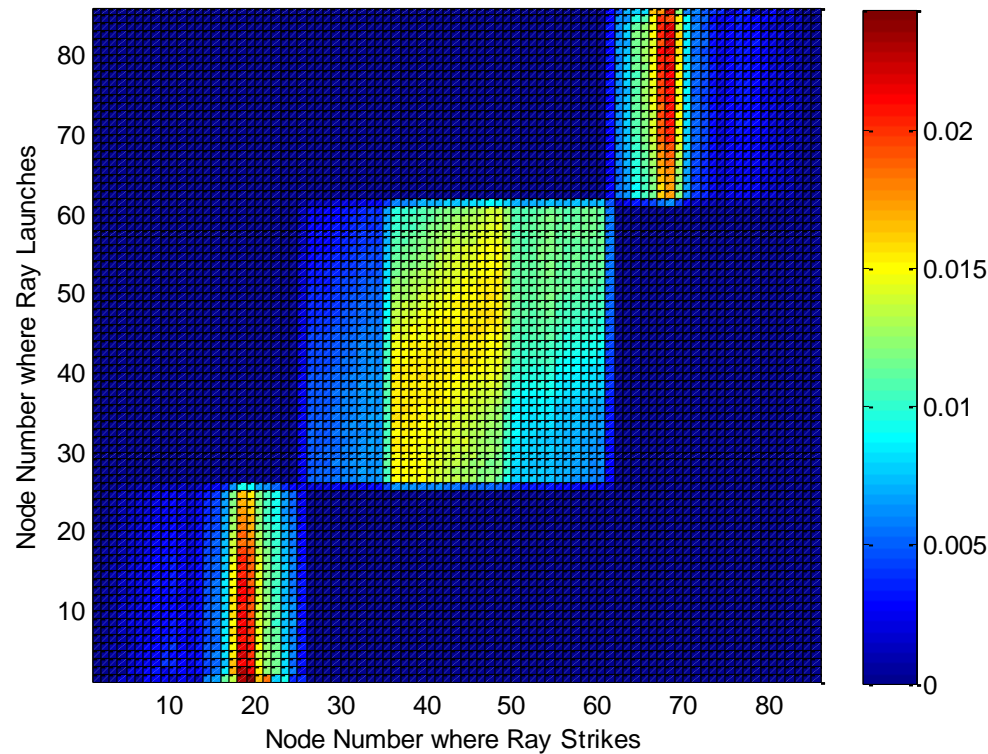
Assume laminar flow with Argon at 500 K and 150 Torr ($Ra_L = 10^6$)

Horizontal Cylinder $\rightarrow h \approx 5.7 \text{ (W/m}^2\text{K)}$

$$h = \frac{k}{D} \left(0.6 + \frac{0.387 Ra_D^{1/6}}{(1 + (0.559/Pr)^{9/16})^{8/27}} \right)^2 \quad (\text{Churchill and Chu})$$

Assume laminar flow with Argon at 500 K and 150 Torr ($Ra_L = 10^6$)

Node-Node Reflected VF, total rays = 30000000

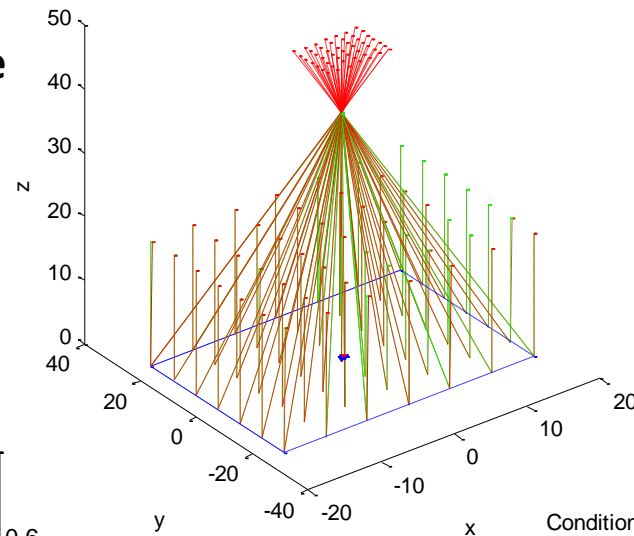


Accuracy Requirements in the Literature

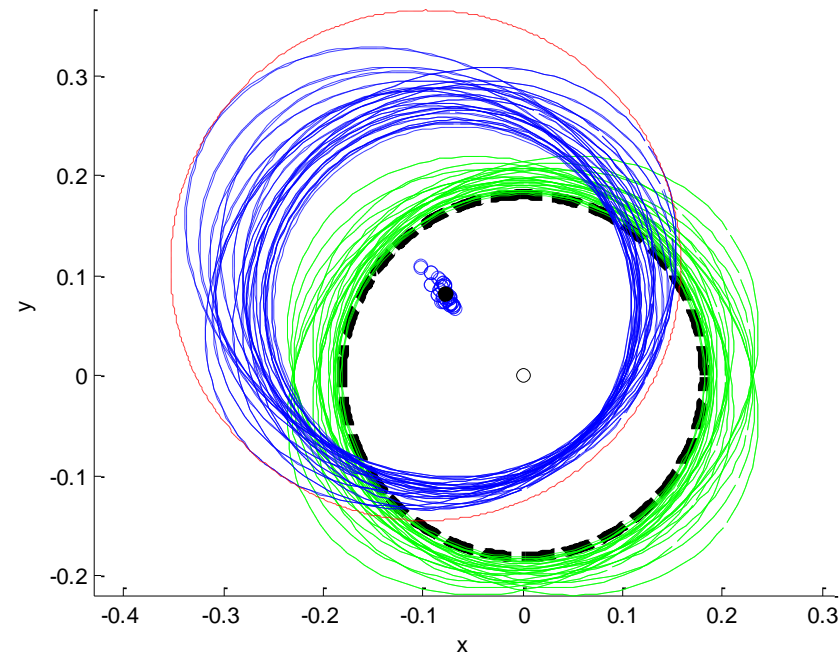
- $\pm 0.3^\circ$ - *Hukuo 1957*
- $\pm 0.1^\circ$ - *Ethridge 1979*
- $\pm 0.5^\circ$ - *Holmes 1995*
- $\pm 0.1^\circ$ - *Kennedy 2004*

Note idea image
for a parabolic
concentrator

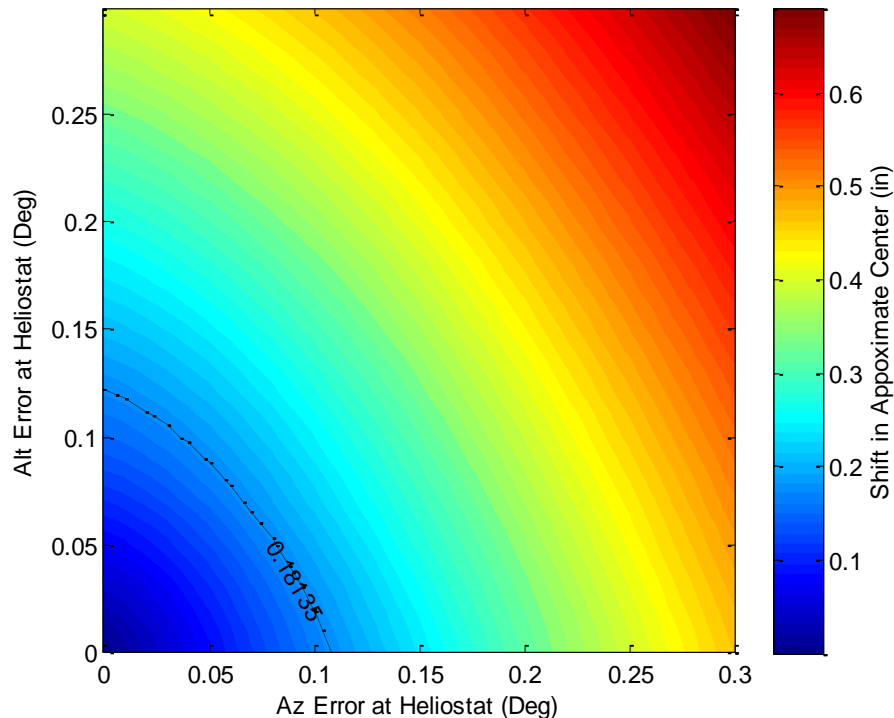
$$d = 2f \sin(\theta_{sun}/2)$$



Conditions at Focal Plane



Displacement in Center Spot vs. Heliostat Error



Hukuo and Mii 1957

FIG. 1 — Section of a parabolic mirror.

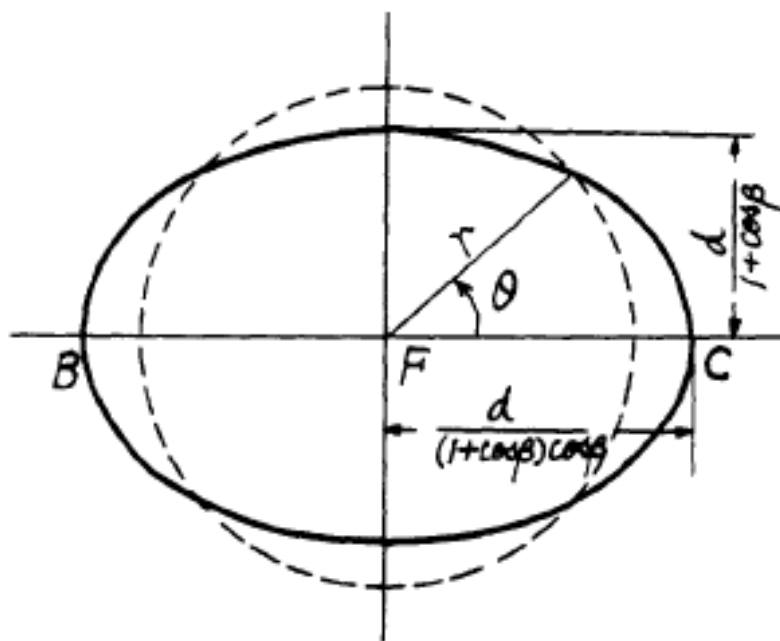
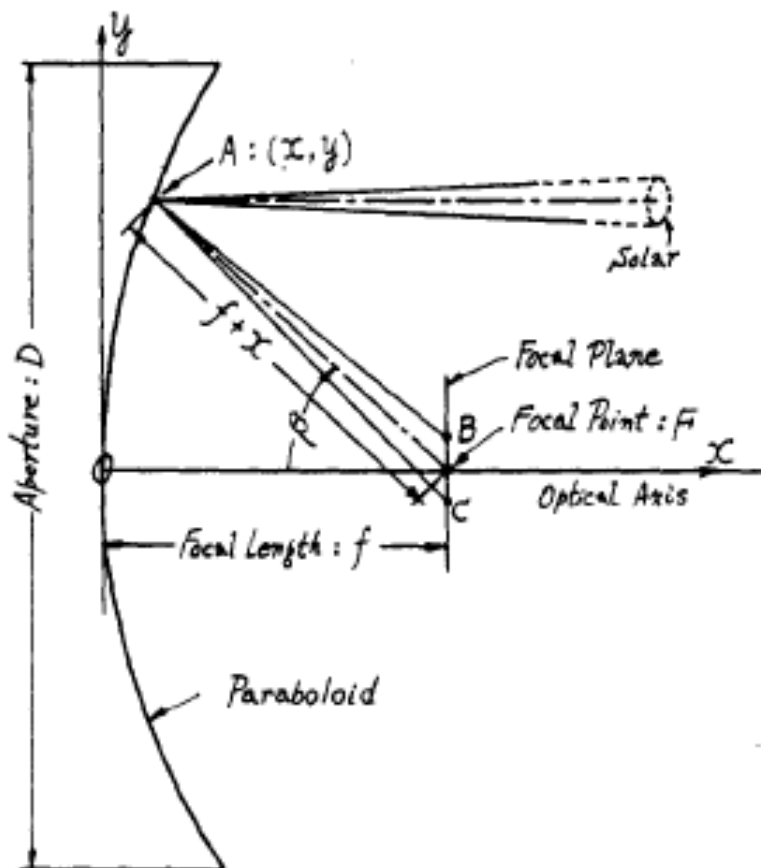
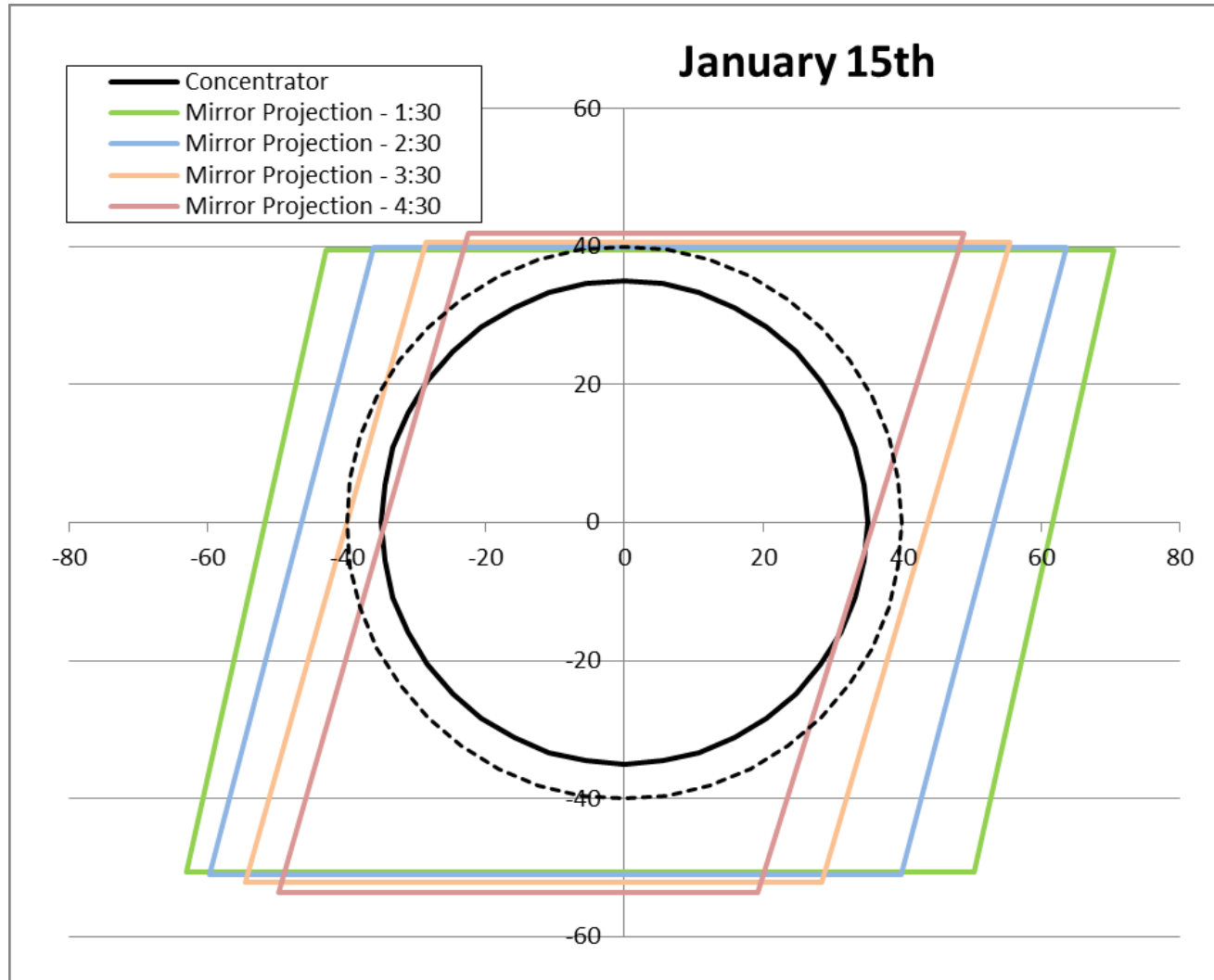
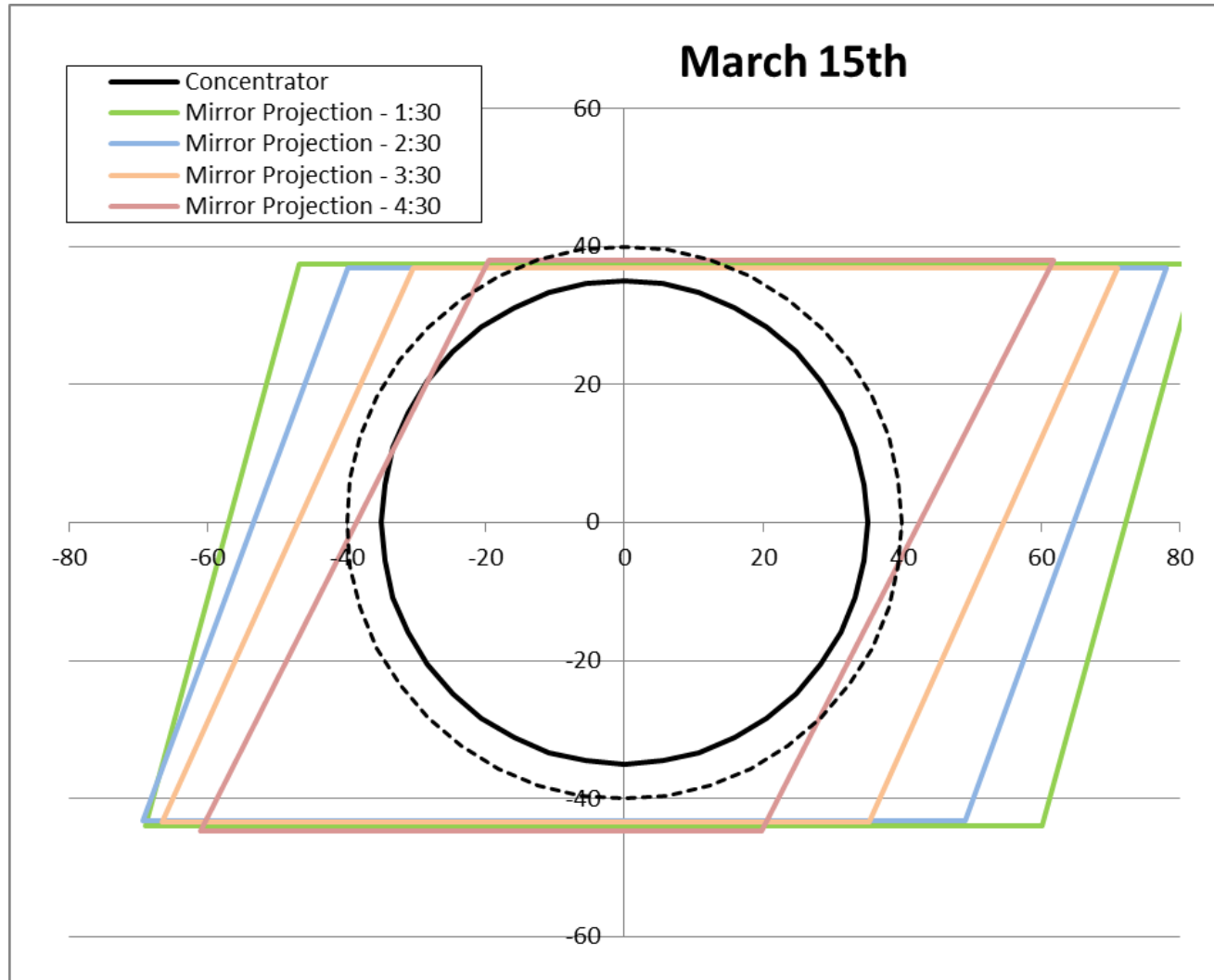
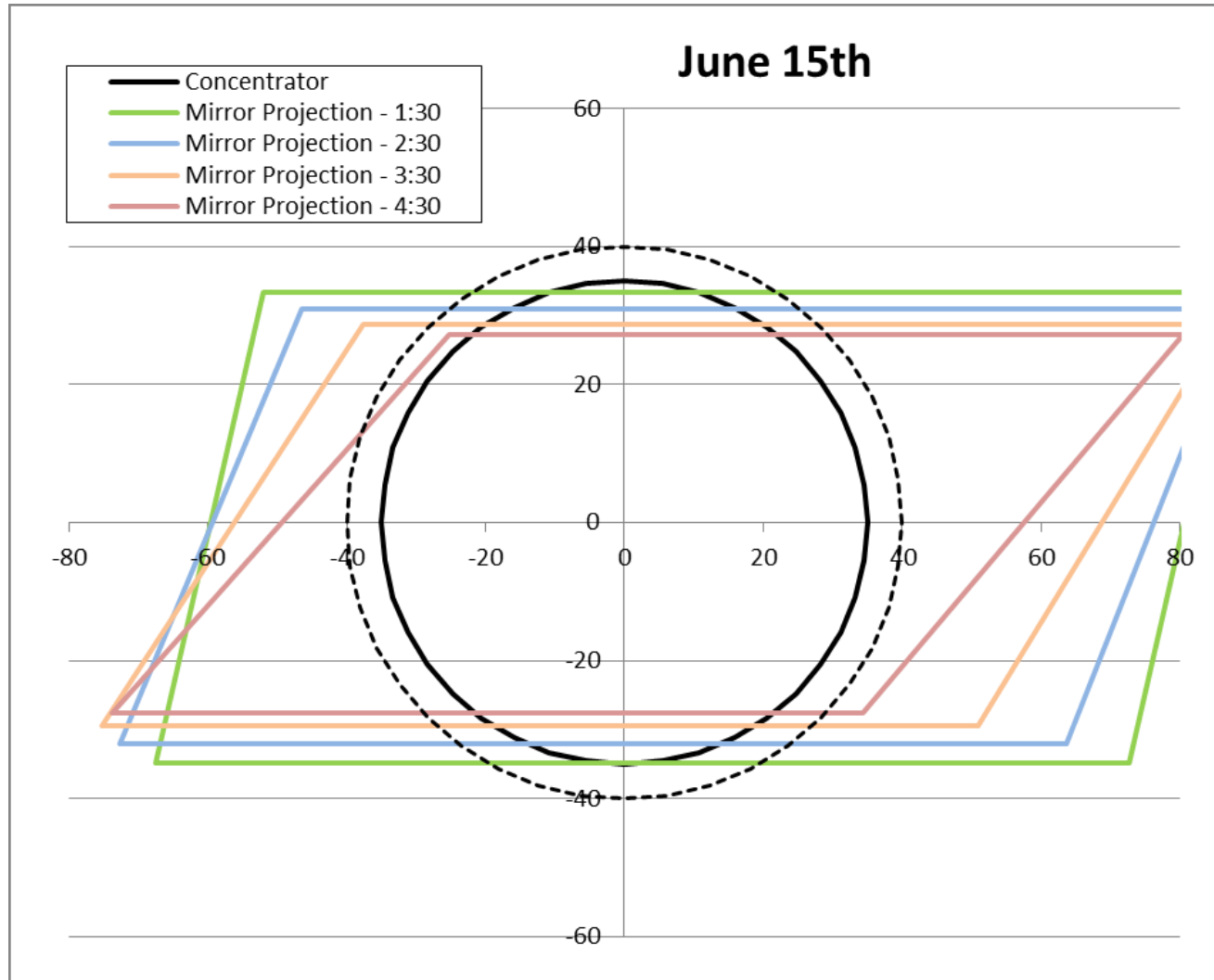


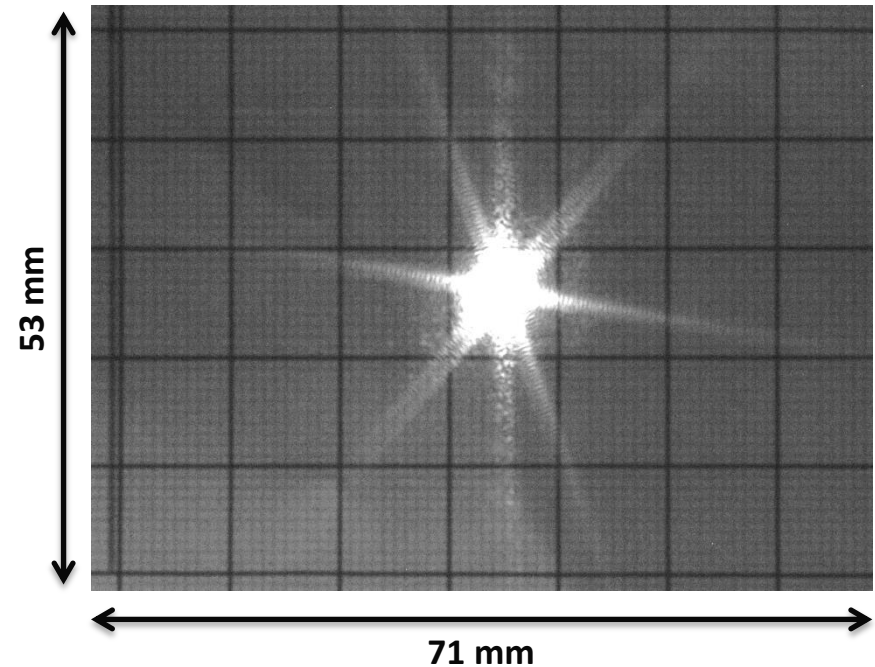
FIG. 2 — Solar image produced by a ray which is reflected by the paraboloid with the angle β .







- Read pixel intensities from CCD after subtracting representative “dark frame”
- Convert using black body calibration from *counts/μs* to W/m^2nm at 980 nm
- Account for reflectivity of pseudo-Lambertian surface
- Convert from W/m^2nm to # of Suns
 - Weight against filter band pass
 - Use ASTM G173 data to scale 980 nm values with the full spectrum
 - Multiply by ASTM G173 standard insolation to get pixel reading in W/m^2
- Compare to locally measured insolation to get map of concentration ratios



Sony ICX445 CCD - 1.2 MP
16-bit mono output format
Images captured at 640 x 480



Solar Thermal w/o Energy Storage	Chemical Thrusters	Electric Propulsion
<ul style="list-style-type: none"> • Eliminated PCM and TPV • Reduced solar collector size • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV 	<ul style="list-style-type: none"> • Astrium Hydrazine Monoprop • Commercially available 1 N and 20 N models • Isp: 220-230 s • Removed thermal energy collection and storage system • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV 	<ul style="list-style-type: none"> • XHT-100 Hall Effect Thruster • 95 W power draw • Isp: 750-1000 s • 3 – 10 mN Thrust • Removed thermal energy collection and storage system • Added photovoltaic panels and batteries • Used NASA year 2020 specific power projections for PV

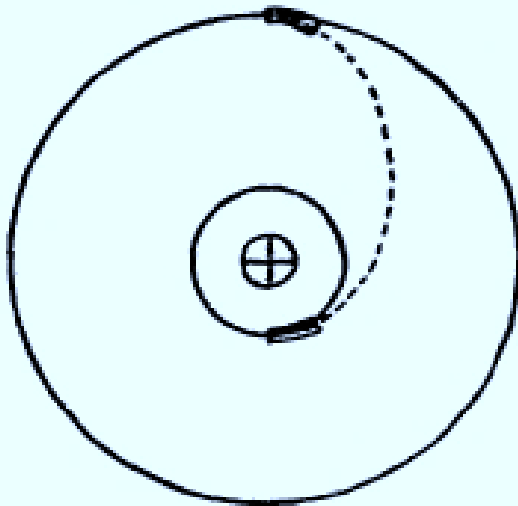
Identical Mass Fractions ($m_{\text{Propulsion \& Power}} = 58\%$)

Total ΔV and Delivery Time are Primary Comparison Metrics

TWO IMPULSE

ONE PERIGEE BURN
ONE APOGEE BURN

$$T/W > 0.01$$



LEO TO GEO

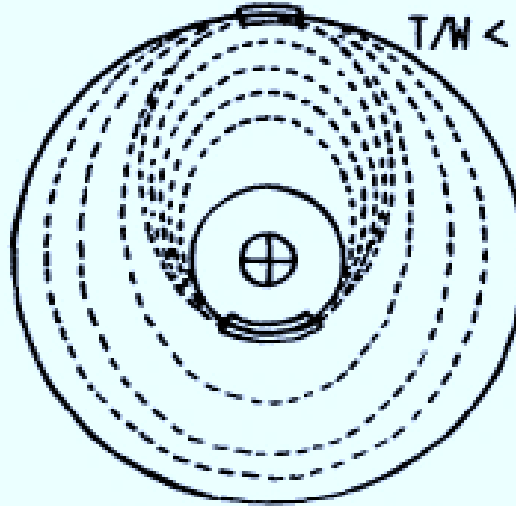
$$14000 \leq \Delta V \leq 17000 \text{ FPS}$$

TRIP TIME < DAY

MULTI IMPULSE

MORE THAN ONE PERIGEE
BURNS AND MORE THAN
ONE "INSERTION" BURNS
NEAR FINAL APOGEE

$$T/W < 0.1$$



LEO TO GEO

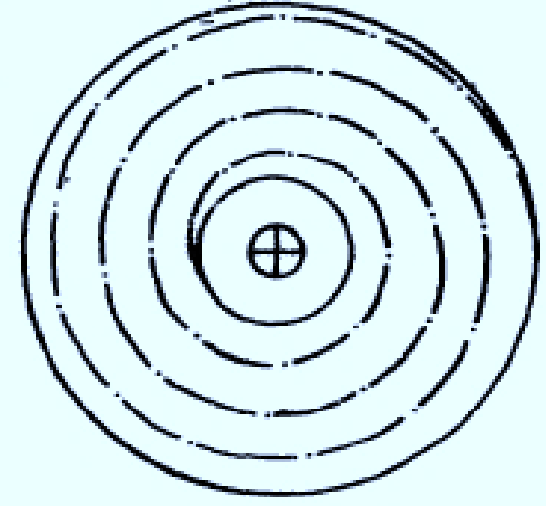
$$14000 \leq \Delta V \leq 19200 \text{ FPS}$$

TRIP TIME > DAYS

CONTINUOUS BURN

SPIRAL TRAJECTORY

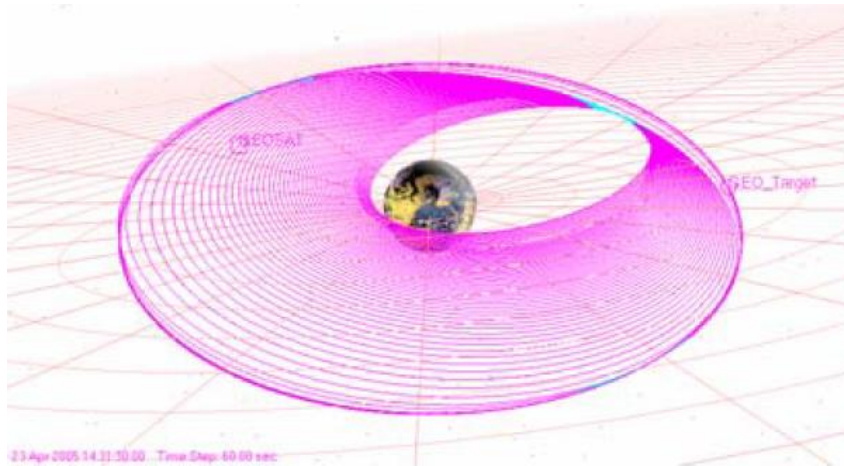
$$T/W < 0.001$$



LEO TO GEO

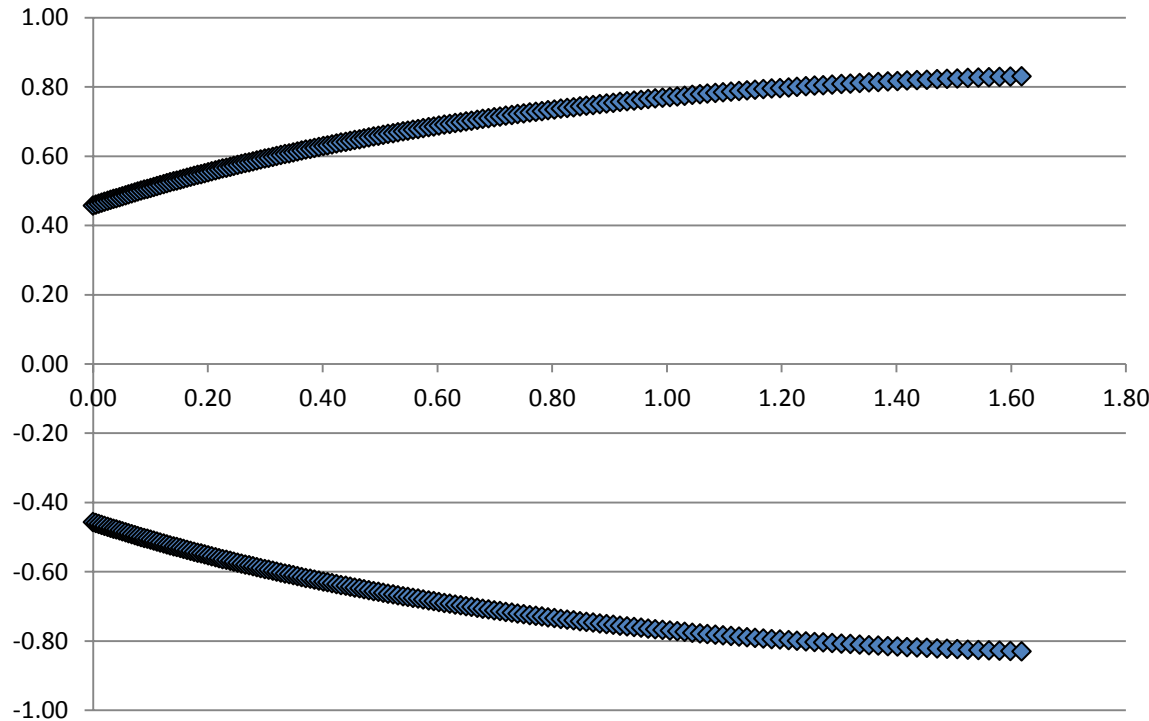
$$\Delta V \approx 19200 \text{ FPS}$$

TRIP TIME > WEEK



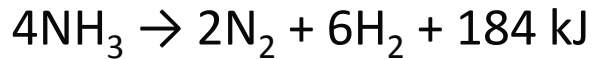
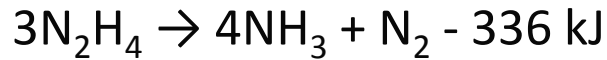
- 10% “On Time”
- 100 kg satellite
- Launch from Ariane 5 into GTO (350 x 35,717 km - 7°)
- Transfer to 0° at 116 °E
- Assumes $\frac{1}{2}$ N thrust and 400 s I_{sp}
- 48 kg for *JUST* solar thermal engine and propellant

Start Date	1 April 2005, 00:00:00.00 (Julian Date 2453461.5)
End Date	6 May 2005, 09:11:16.96 (JD 2453496.88)
Elapsed Time	35 days, 9 hrs., 11 min.
Number of Maneuvers	58 (51 apogee kicks, 7 plane changes at node crossings). Two-orbit “hold” of 42 hrs., 20 min. introduced after apogee kick 48 to attain proper orbital phasing at GEO
Total Velocity Change	1,761 m/s
Propellant Consumption	36.184 kg
Final Mass	63.816 kg
Engine “On-Time”	80 hrs., 33 min.

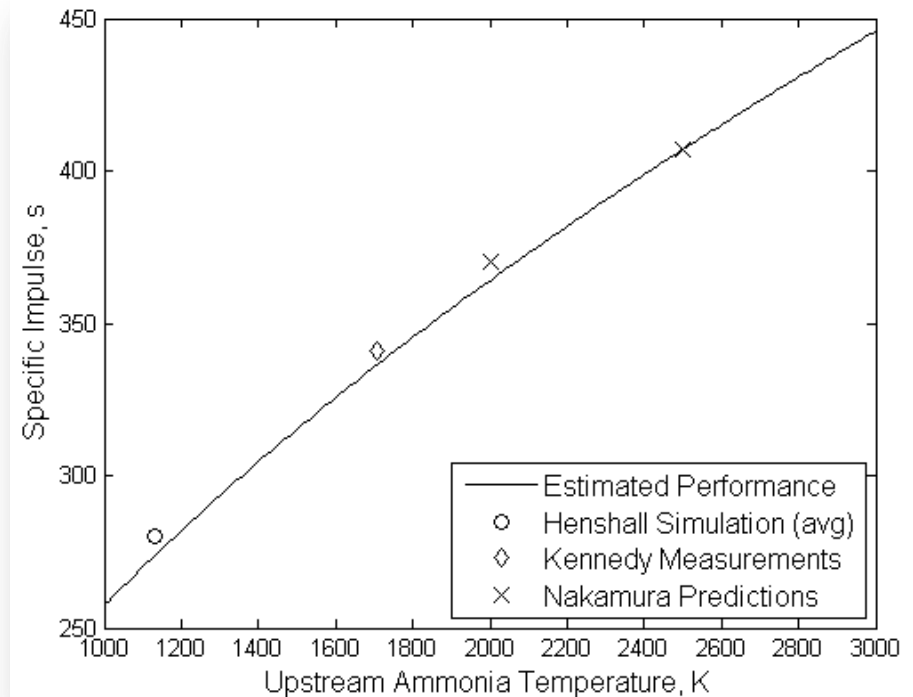


- Defined by parametric equations given by *Welford and Winston 1978*
- **CAN NOT** be used to increase power due to low f/d ratio for the concentrator
- **CAN** be used to increase concentration ratio

Diameter	Max Angle	Minimum Diameter	% Area Increase	Max Ratio	Minimum Spot	Spot Change	C Ratio Change
70	33.0	1.66	0%	3.24	0.914	0.84	5%
75	35.162	1.81	15%	2.99	1.046	1.09	-16%
80	37.7	2.09	32%	2.67	1.220	1.49	-29%



Net 1.6 MJ/kg



α_D

I_{sp}

0

253

0.2

274

0.4

289

0.8

312

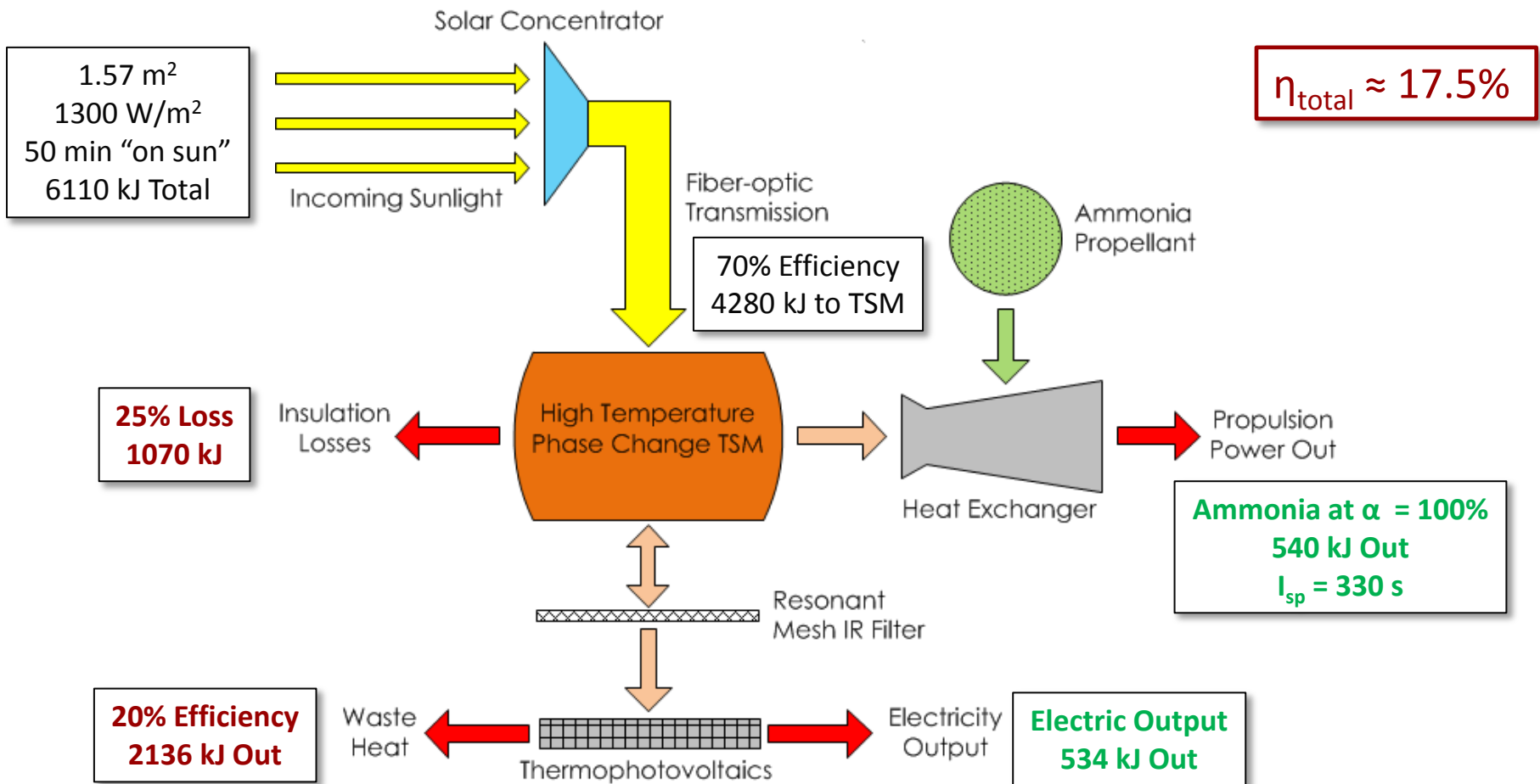
1

322

- Incomplete dissociation will lower performance
- Equilibrium calculations for 1500 K solar thermal thruster (*Colonna et. al. 2005*)
- Note, hydrazine thrusters typically have $\alpha_D \approx 55\%$

$$V_e = I_{sp} g_o = \sqrt{\frac{T_o R}{M} \frac{2\gamma}{\gamma - 1} \left[1 - \left(\frac{p_e}{p_o} \right)^{\frac{(\gamma-1)}{\gamma}} \right]}$$

For each 200 km Orbit





- Satellite is sized for a 200 km circular orbit
 - Storage sized for approx. 36 min eclipse
- Assumes 20% total electrical system efficiency
- Assumes 70% thermal collection efficiency
- Approximates impulsive burn profile with a 5% firing rule